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DRAFT FINAL
ESTIMATION OF GROUNDWATER FLOW THROUGH AND PCB LOSSES FROM THE PROPOSED CONFINED DISPOSAL FACILITY C
NEW BEDFORD HARBOR SUPERFUND SITE
New Bedford, Massachusetts

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Prepared for

U.S. Army Corps of Engineers
New England District
Concord, Massachusetts

Prepared by

Foster Wheeler Environmental Corporation
133 Federal Street
Boston, MA 02110

Revision	Date	Prepared By	Approved By	Pages Affected
0	5/8/01	B. Jacobs A. Tognon	A. Ikalainen	All

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Flow volumes through the proposed Confined Disposal Facility C (CDF-C) at New Bedford Harbor were estimated based on groundwater flow models of the CDF in the regional flow field and local tidal characteristics. Both systems were simulated using the MODFLOW numerical code and the Groundwater Vistas simulation interface.

The regional aquifer was represented using a full three dimensional characterization of the local aquifer extending from the harbor on the east to the western extent of significant valley deposits. Borings from field investigations related to the CDF design and prior construction were used to determine the bedrock elevation, and the location, thickness and elevation of stratified deposits, clay strata and artificial fill. For the most part, the clay is present under the harbor, thinning out to the west. The bedrock is deepest underlying the harbor and slopes upward to the west. The stratified deposits fill the bedrock valley and are therefore deepest in the center of the valley and thinning as the bedrock elevation increases.

The hydraulic conductivity of the clay strata and stratified deposits were set based on slug tests and the calibration to measured piezometric head data. The hydraulic properties of the dewatered sediment, CDF sand, and barrier wall components were established from the Foster Wheeler CDF C design.

The following eight simulations were performed of the regional flow model:

1. lined CDF-C, base case
2. unlined CDF-C base case
3. CDF-C lined only on west side
4. lined CDF-C, with 10,000 square foot hole in the underlying clay
5. lined CDF-C with double permeability in underlying clay
6. lined CDF-C with recharge into CDF increased by factor of 100
7. unlined CDF-C, with 10,000 square foot hole in the underlying clay
8. unlined CDF-C with double permeability in underlying clay

For each case, the 30-year and 100-year flow volume in and out of each of the components of the CDF were presented to summarize the results.

The piezometric head inside CDF-C was found to recover from its initial elevation of –1 feet to an equilbrium elevation in excess of 1 foot within a year. This caused an initial inflow into the CDF-C sediment layer during that first year. The liner reduced flows from the CDF sand layer to the harbor from 7.1×10^6 ft^3 over 100 years to 2.9×10^4 ft^3 over that same period. The flow through and from the upper sediment layer within CDF-C was not impacted to the same extent as the sand layer as the barrier permeabilities provided only a small increase in resistance to flow relative to the low permeable dewatered sediment. The flows from the sediment layer of the CDF to the harbor decreased on addition of the liner from 7.1×10^3 ft^3 to 2.0×10^3 ft^3 over the 100 year simulation due to an increase in the equilibrium head elevation in the lined CDF scenario.

Holes in the clay liner and/or increased permeability in the clay liner, increased flow through the sand base of the CDF, but did not impact significantly the outflows from the sediment layer of the CDF. Increasing the recharge by a factor of 100 increased the sediment outflow from the sediment layer by a factor of 13 over the 100 year simulation.

The tidal model was constructed as a two dimensional vertical strip representing a typical east-west profile. It extended from the harbor , through the CDF to its western boundary. The base elevation is -4 feet, overlain by 3 feet of sand and four feet of dewatered sediment within the CDF. Both the unlined and lined CDF designs were evaluated.

The piezometric head within the lined CDF varies on the order of 0.001 feet, with total CDF outflow from the CDF amounting to 2.1×10^4 ft^3 over the 100 year period. The unlined CDF operates very differently than the lined CDF, with significant tidally derived head changes in the CDF sand and a total outflow of 5.5×10^6 ft^3 over that same period. There is less change in piezometric head in the overlying sediment, however this creates oscillating vertical flows between the CDF sand and the overlying contaminated sediment that would tend to spread the PCB contamination to the CDF sand. The total estimated water volume flowing from the dewatered sediment (layer 4) to the underlying sand (layer 3) over that period would be 3.9×10^6 ft^3 for the lined CDF and 7.1×10^3 ft^3 for the unlined CDF over the 100 year simulation.

PCB losses were estimated from CDF C using the modeled groundwater flows and the groundwater outflows from the tidal simulation. Analogous to previous loss estimates developed for the Record of Decision (ROD), the PCB losses were estimated by using a pore water concentration of PCB with the groundwater flow determined from the groundwater modeling.

The PCB pore water concentration used is based on batch leaching tests conducted by the United States Army Corps of Engineers Waterway Experiment Station, which represent a hydraulically placed dredged sediment with a composite PCB sediment concentration of 1500 to 2150 mg/kg. The use of the PCB pore water concentrations from the batch leaching tests, although not uniquely specific to dewatered sediment placement, are conservative when considering that the column leaching tests conducted on the same sample were of an order of magnitude lower. However, pore water concentrations in dewatered sediment could be higher which would make these estimates conservative.

The PCB losses estimated from the groundwater modeling suggested that the mass of PCB exiting the dewatered sediment in the CDF would not exceed the 7.8 kg limit reported in the ROD. Conversely the PCB losses estimated from the tidal simulation suggests that the mass loss of PCB existing the CDF will result in a net loss of 9 kg of PCB over 30 years, exceeding the limit reported in the ROD.

1.0 INTRODUCTION

A model of groundwater flow was constructed to estimate the flow through the proposed confined disposal facility C (CDF-C) of the New Bedford Harbor Superfund Site. The goal was to estimate the mass loss of polychlorinated biphenyls from the CDF for several design alternatives. Designs presently under consideration include an unlined facility, a facility with a circumferential barrier wall, and a barrier wall on the west side of the CDF.

The groundwater model will be used to directly estimate the volume of water that will escape from or pass through the CDF-C over a 100-year period. Based on the results of lab scale leaching tests performed on sediment from the harbor, a concentration will be associated with the estimated water volume to determine the PCB mass loss. This mass loss will be used to determine the cost effectiveness of various strategies in reducing losses and enable comparison of the CDF-C performance with the design goals described in the record of decision (ROD) for O.U. #1, September, 1998.

The approach taken to estimate the total water volume loss was to consider separately the long-term fluxes due to regional flows and flows generated by tidal variability in the ground water elevation. This approach depends on the approximate linearity of the system, enabling superposition of solutions based on different boundary conditions.

All simulations were performed using the United States Geological Survey finite difference code, MODFLOW (McDonald and Harbaugh, 1988). GW Vistas (ESI, 1999) was used for data entry, preparation of report graphics and estimation of CDF-C flow volumes.

2.0 HYDROGEOLOGIC SETTING

The location of the proposed CDF-C, shown in Figure 1, lies on the west bank of the Acushnet River. This portion of the river is also referred to as the Upper New Bedford Harbor. Contours in Figure 1 show the thickness of stratified deposits as interpreted in Williams and Tasker (1978). This portion of the aquifer is relatively shallow and largely isolated from water bearing soils in the remainder of the watershed. The bulk of the aquifer is comprised of glacially derived stratified sands deposited within a narrow bedrock valley. The sand deposits thin out to the west due to the relatively steep bedrock slope and overlying glacial till material.

A relatively impermeable organic clay material is encountered underlying the harbor and at the location of some onshore borings. Offshore the clay thickness varies between 4 and 14 feet, while onshore the clay, where present, varies between 4 and 6 feet (Foster Wheeler, 2000).

Flow is typical of New England bedrock valley aquifers. The aquifer is bounded by elevated bedrock and till to the west. The bedrock and till provide relatively little groundwater storage capacity and are relatively impermeable materials. The aquifer recharges in the western upland area underlain by the stratified sand deposits and flows toward the low-lying Upper Harbor. Figure 2 shows piezometric head observations from monitoring wells across the aquifer. With several exceptions the heads are generally greater to the west and decrease to the east – indicating flow from west to east. Typically, in valley aquifers of this type, flow is largely horizontal, tending downwards in the upland recharge zones and tending upwards in the lowlying discharge zones. In this case, the aquifer recharges in the west and discharges through the clay strata into the harbor.

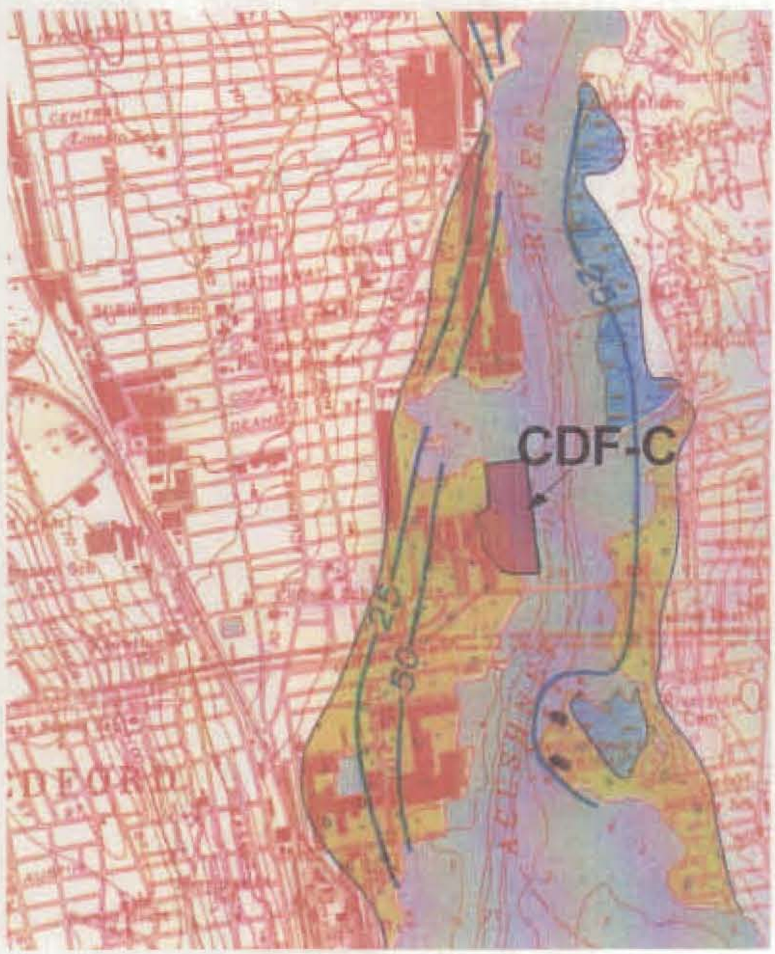


Figure 1. Thickness of stratified deposits and proposed CDF-C location (adapted from Williams and Tasker, 1978)

Because the harbor is wide relative to its upstream width the water level is anticipated to be nearly constant over the length of the simulated domain. Figure 3 shows the simulated water surface elevation north of the tidal barrier opening and north of CDF-C (USACE, 2001). The barrier is to the south of the model's southern extent, while a point north of CDF-C would be in the northern half of the model. These results indicate that the water surface elevations are similar for these two locations. The low tide at the northern end of the estuary (not shown) is approximately ½-foot higher than at these other locations, but this is to the north of the model extent. Flow is therefore largely driven by topography, with the predominant direction of groundwater flow perpendicular to the direction of surface flow in the harbor.

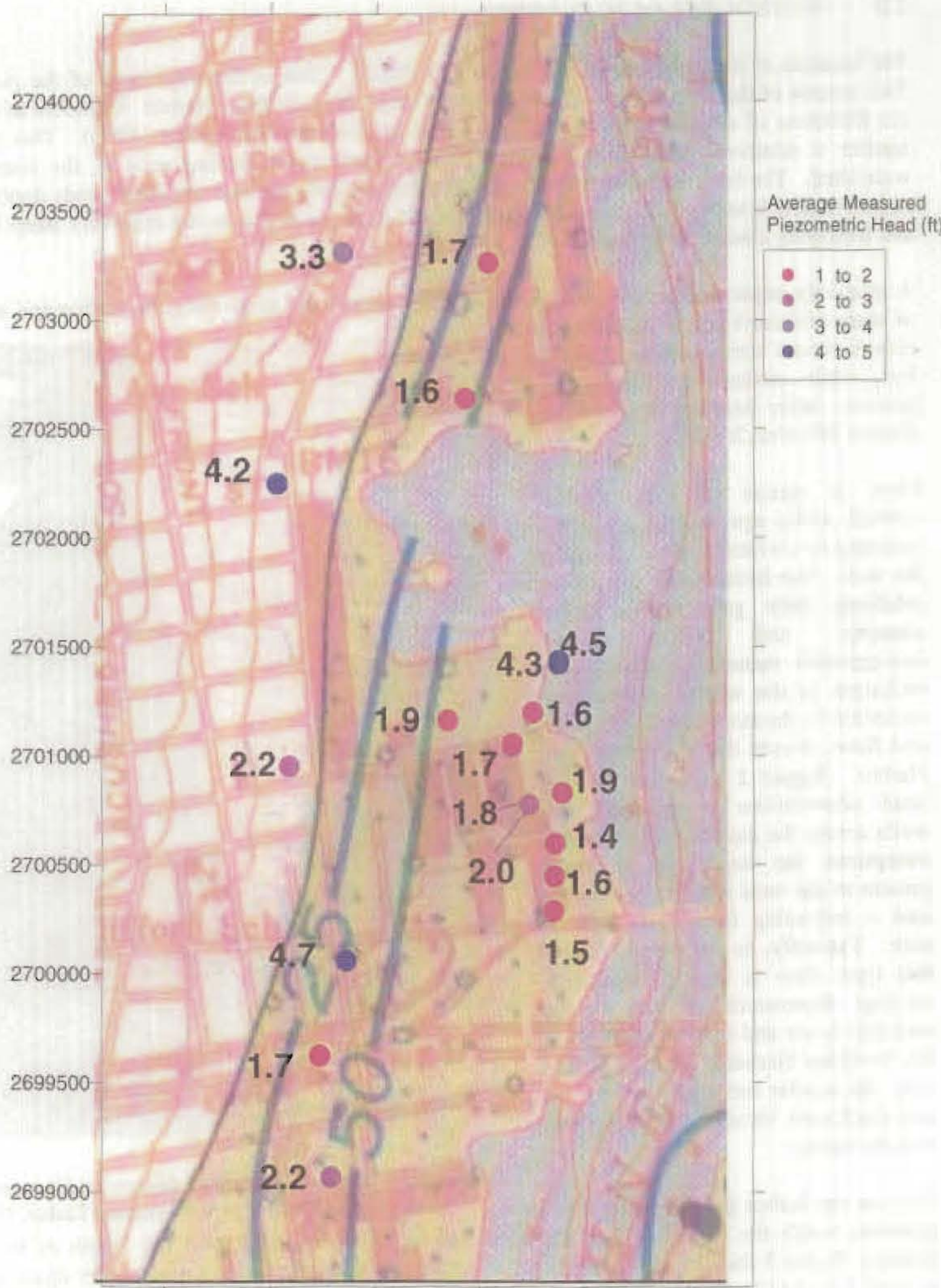
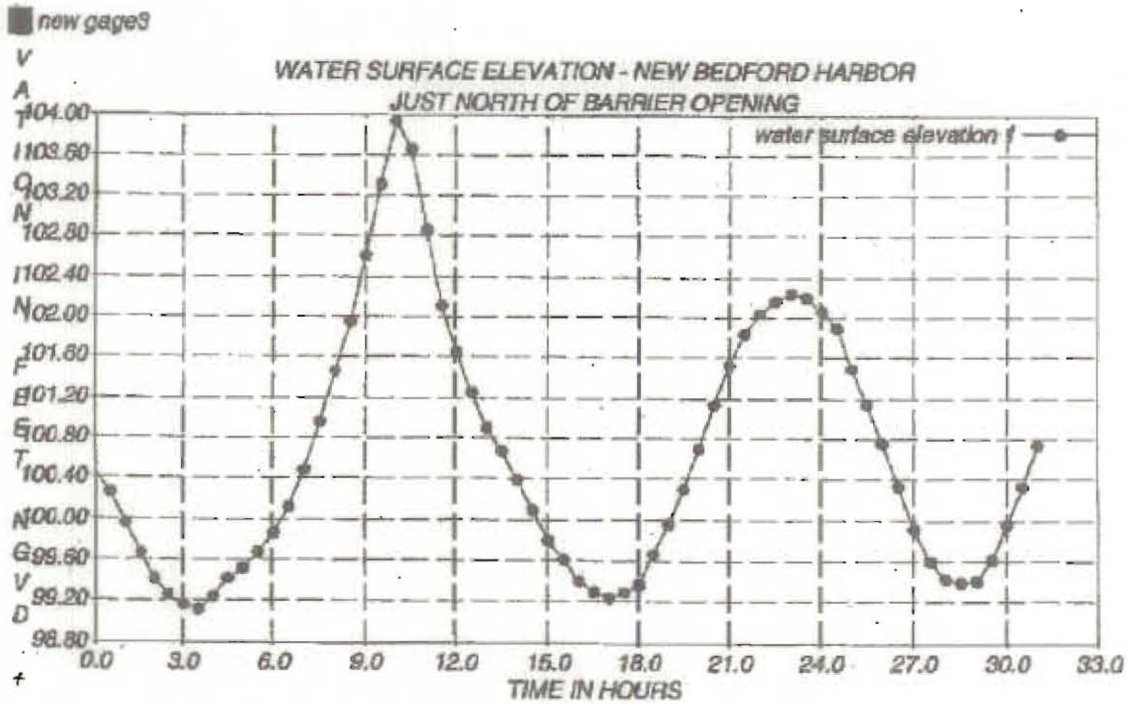


Figure 2. Average piezometric head observations from Foster Wheeler Env. (2000) and Haley and Aldrich (1991).



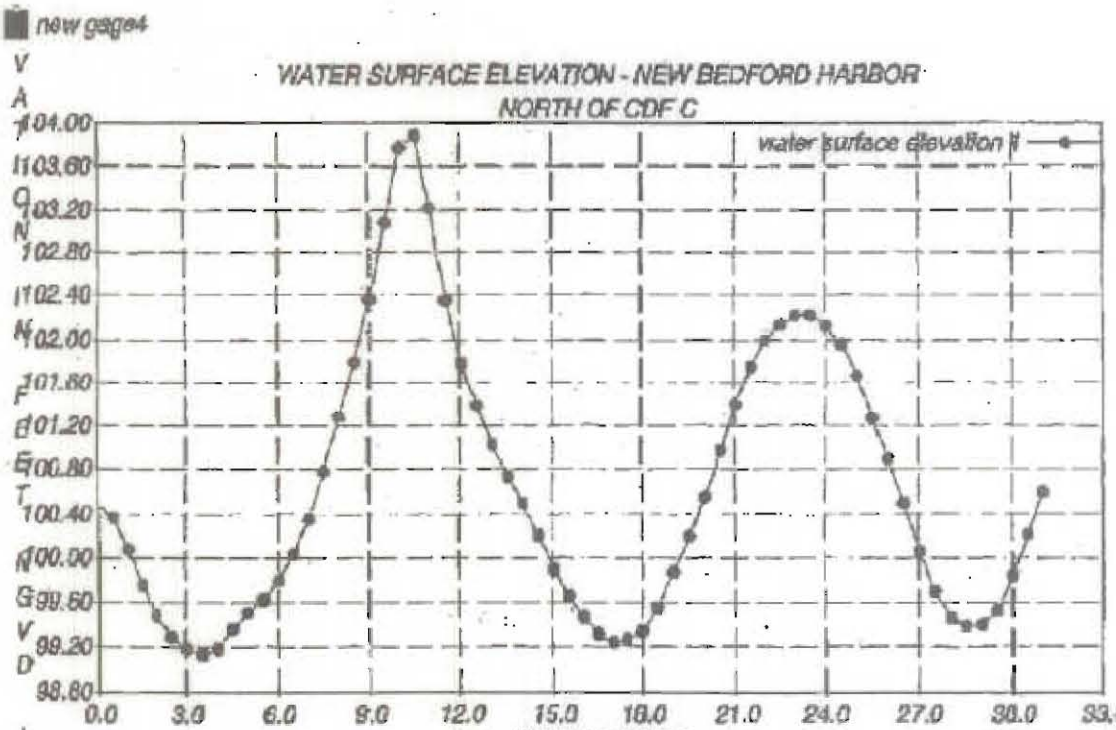


Figure 3. Simulated water surface elevation (ft) north of the New Bedford Harbor tidal barrier and north of CDF-C (Geib, USACE, personal communication).

3.0 LONG TERM MODEL

The long-term model is intended to represent the CDF-C response to regional flow under average conditions. Seasonal variability and variability between wet and dry years are not represented in the model. The effects of this variability are considered to be second-order effects, which are considered to have less effect on model results than other factors. Other factors that affect model results are estimated hydraulic conductivity of the emplaced sediment, variability in actual clay thickness and the estimated effective permeability of the HDPE liner.

3.1 Model Domain and Horizontal Discretization

Figure 4 shows the model domain and the numerical grid used in solution of the groundwater flow field. The model's eastern edge lies in the center of New Bedford Harbor. As this is a valley aquifer, the center of the harbor may be approximated as a specified zero-flow boundary (groundwater divide). Groundwater east of this line will be travelling in the opposite direction from east to west and discharging into the harbor.

As mentioned above, the groundwater flow is considered to be largely driven by topography with flow from west to east. The northern and southern domain boundaries are sufficiently far from the proposed CDF-C, that stresses imposed at the CDF are unlikely to cause detectable changes in flow at these boundaries. The boundaries also roughly coincide with the northern and southern extent of significant stratified deposits as indicated in Figure 1.

The western domain boundary lies at the approximate western boundary of stratified deposits indicated in Figure 1. Significant groundwater flows from areas further west are not likely due to a rising bedrock surface and the presence of a dense glacial till overlying the bedrock.

The grid nodes are 25 by 25 feet in the area of interest in and around the CDF, gradually increasing to the north and south to a height of 100 feet. This horizontal discretization is more than adequate to represent the spatial variability of head within the domain.

3.2 Vertical Discretization

The model was constructed with six layers. Figure 5 shows the model strata depicted on an east-west profile roughly through the center of the proposed CDF-C (row 70). From the bottom up, layers 5 and 6 represent the stratified sand deposits. Layers 3 and 4 represent the clay strata found offshore and at some onshore locations. Figure 6 shows the area represented as having clay present along with the recorded clay thickness at individual soil borings. In those areas where borings indicate that the clay strata is absent, the nodes were assigned hydraulic properties consistent with the overlying fill deposits.

Layers 1 and 2 represent artificial fill material over most of the onshore model domain. Within the CDF, layer 2 is used to represent the sand layer that is to be introduced directly over the clay layer. Layer 1 within the CDF represents the dewatered contaminated, dredged sediment.

Layer 2 offshore nodes are assigned a specified head boundary condition at the mean tide elevation of 0.55 feet, NGVD. The hydraulic conductivity of nodes in this layer are set to very high values to ensure that head losses across the clay layer are derived from the clay thickness and permeability and not that of Layer 2.

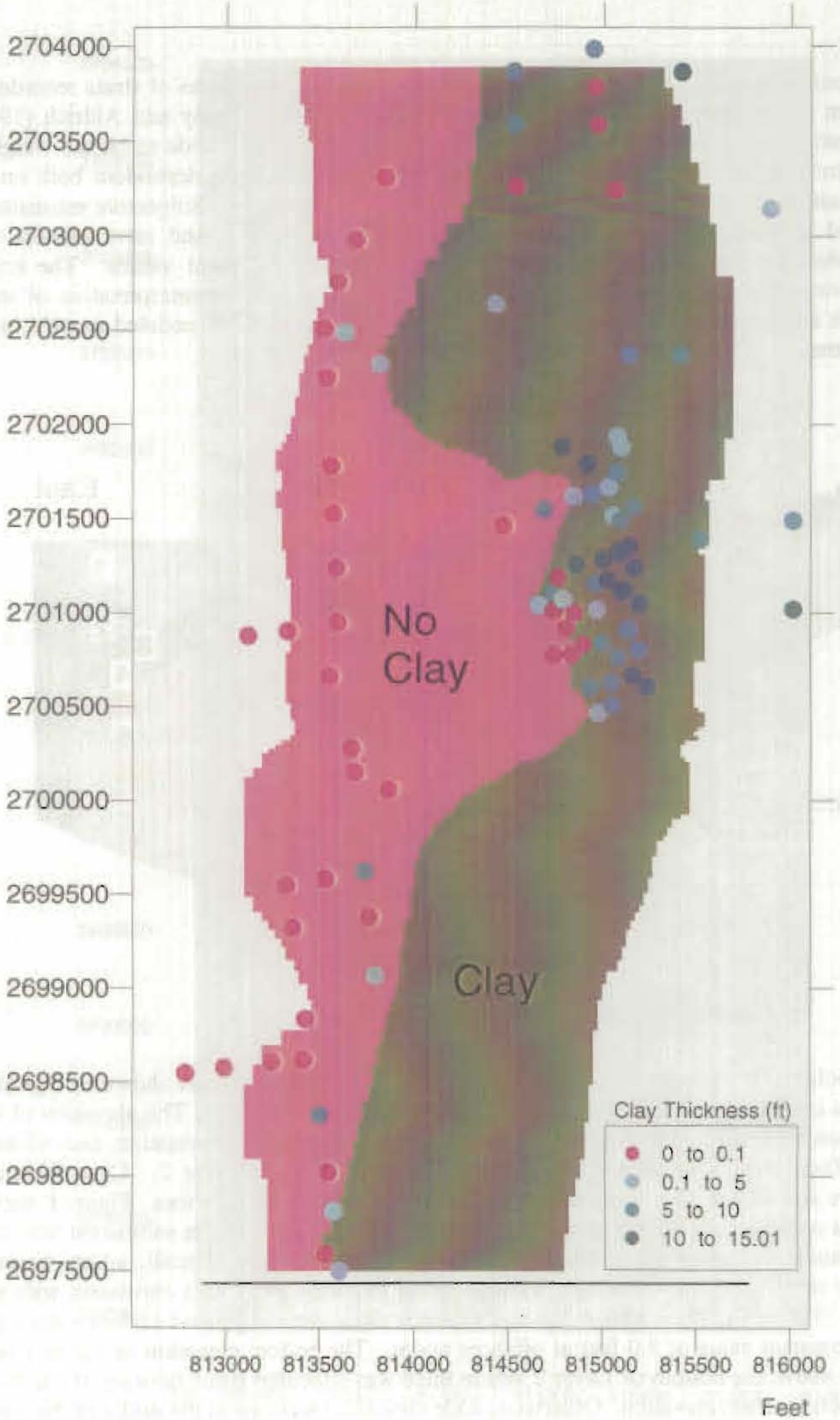


Figure 6. Areal coverage of simulated clay strata and measured clay thicknesses.

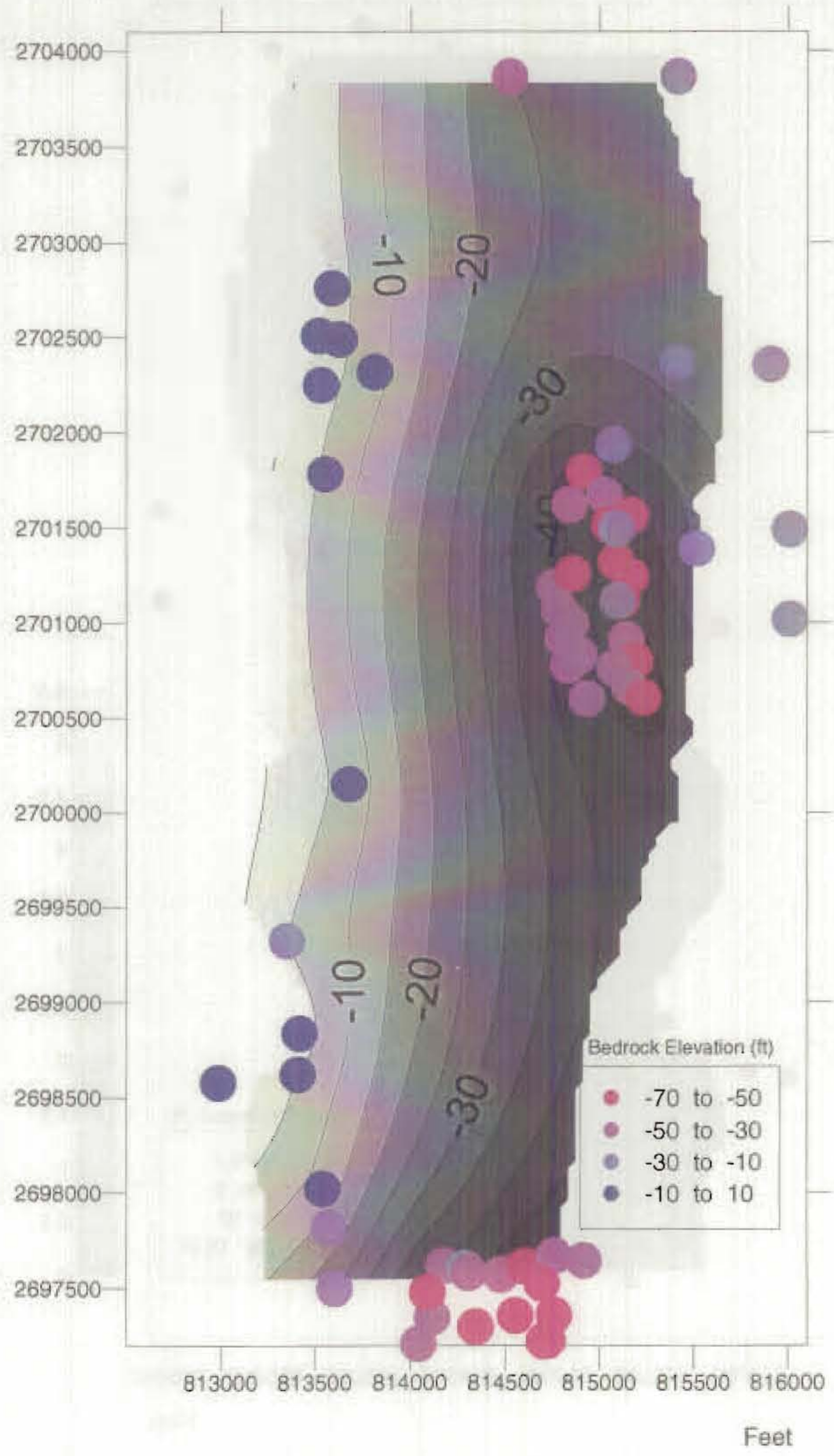


Figure 7. Contours of interpolated bedrock elevation and symbol plot of measure bedrock surface elevation.

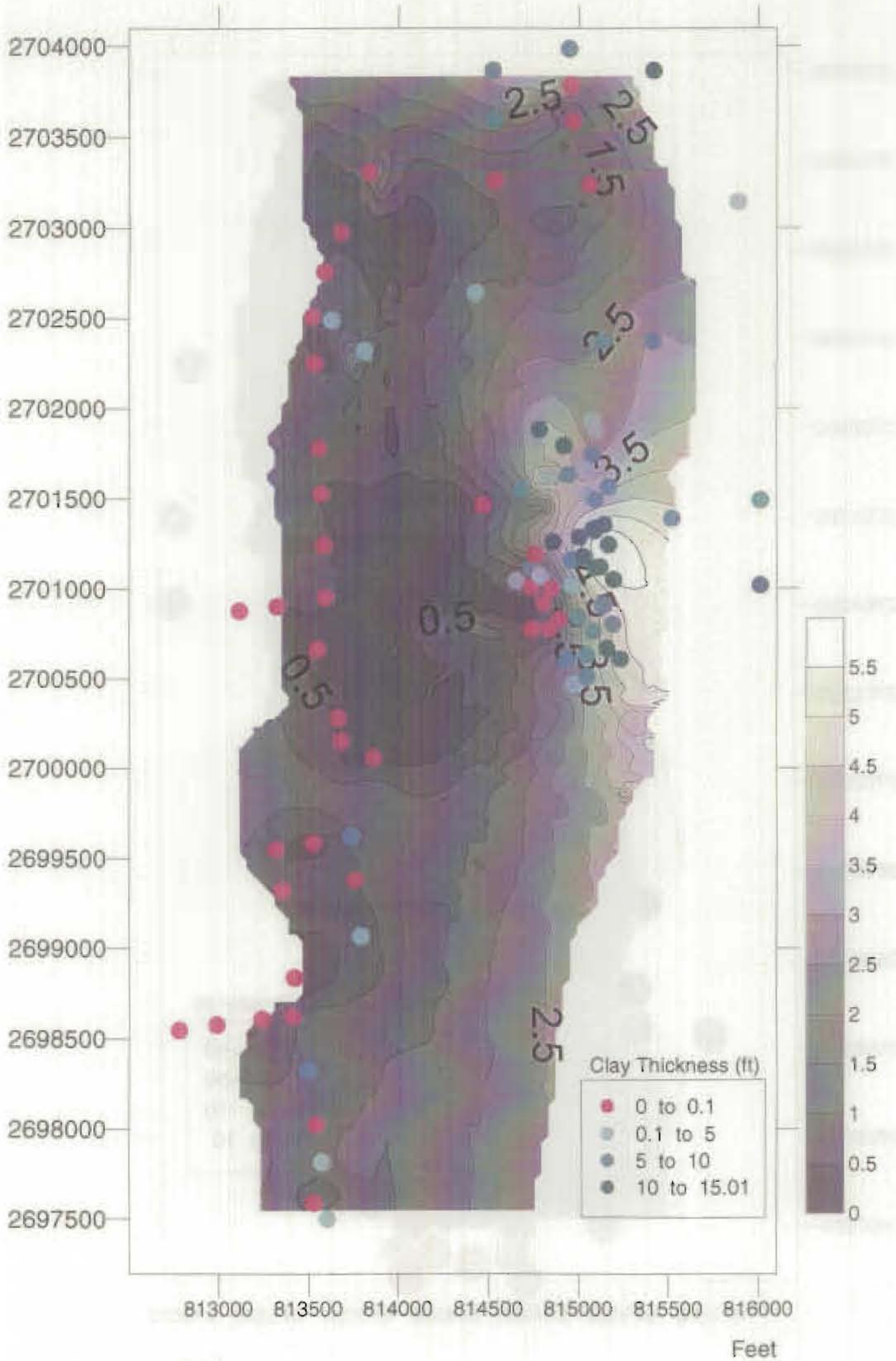


Figure 8. Contours of interpolated clay thickness (Layers 3 and 4) and symbol plot of measured clay thickness.

3.3 Boundary Conditions

The boundary conditions follow naturally from the description of local hydrogeology presented in Section 2 above. The western boundary nodes are zero-flux boundaries as they bound areas of elevated bedrock and till. This is typical of New England bedrock aquifers and consistent with an understanding of flow represented in Massachusetts guidelines for estimation of contributing area to wells. The northern and southern boundaries are considered to be roughly aligned with the direction of flow and were therefore also assigned a zero-flux boundary condition. These boundaries also roughly coincide with the northern and southern extent of stratified deposits shown in Figure 1.

At the eastern domain boundary, in layers representing the clay strata and stratified sand deposits, the nodes are also zero flux due to flows from the aquifer underlying the eastern bank. Offshore nodes of Layer 2, the layer above the clay deposits, are assigned a specified head boundary condition. These nodes, shaded blue in Figure 9, are assigned a piezometric head of 0.55 feet, NGVD – equivalent to the New Bedford Harbor mean tide elevation.

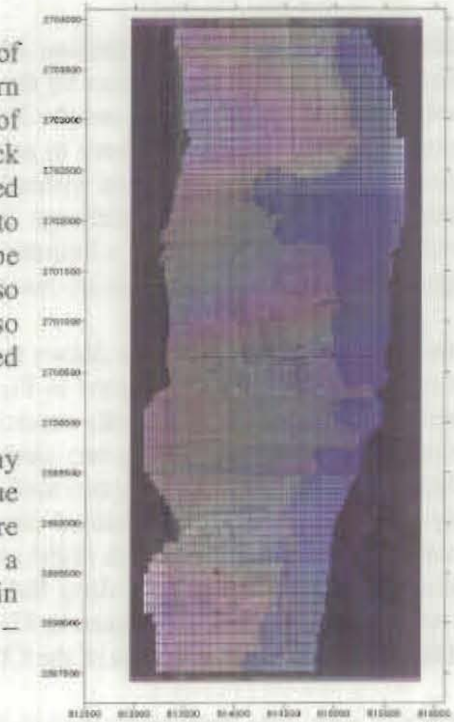


Figure 9. Specified head nodes from Layer 2 indicated in blue.

3.4 Recharge

Bent (1995) presents estimates of recharge to several southeastern Massachusetts aquifers composed of stratified sand deposits like those found in the model domain. The recharge rate in those largely undeveloped aquifers ranged between 23.8 and 25.2 inches per year. In the present case, the model domain is largely developed with a significant portion occupied by impervious surfaces. Storm drainage systems in urban settings of this type reduce significantly the portion of water that would otherwise recharge the aquifer.

The proportion of impervious surface was estimated for discrete zones within the model domain. The recharge within each zone was then assigned a value equal to the product of the undeveloped recharge rate, 23.8 inches per year, and the fraction of unpaved surface. The location of zones of constant recharge and the value of recharge in inches per year are shown in Figure 10. The average recharge rate over the onshore nodes is 6 inches per year.

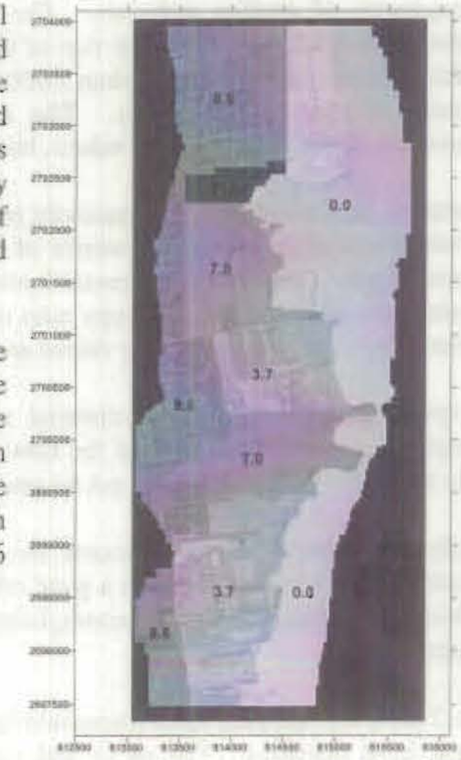


Figure 10. Simulated aquifer recharge rate in inches per year.

3.5 Calibration

Calibration involves the modification of simulated properties to obtain a reasonable representation of measured flow field characteristics by the simulated flow field. In this case, the hydraulic conductivity of the clay strata (Layers 3 and 4) and the hydraulic conductivity of the stratified sand deposits (Layers 5 and 6) were modified by trial and error to match simulated and observed piezometric head values. It should be understood that the calibrated hydraulic conductivities are determined during calibration for a given recharge distribution. If the recharge is not accurate then the modeled hydraulic conductivities will likewise be inaccurate. This is a limitation of all groundwater modeling investigations, however it is our judgement that the recharge rates are reasonably accurate.

Water table measurements were drawn from both Haley and Aldrich (1991) and Foster Wheeler (2000). The measured values are presented in Figure 2 and Table 1. Foster Wheeler (2000) notes groundwater elevation measurements at 9 wells recorded over the period of October through December 1999. They also report measurements over a two week period for two wells, MW-4A and MW-5, in the existing CDF embankment. The head in these two wells is approximately 2 feet higher than in other nearby wells. It is likely the embankment has subsided since the wells were surveyed originally. The monitoring wells documented in Haley and Aldrich (1991) were installed as part of an investigation of soils for the planned extension of a wastewater main along Belleville Avenue. These wells were constructed in February 1991 and water table measurements taken in March and April 1991. These wells were in general further inland than the wells constructed as part of the CDF-C investigation.

A series of slug tests were performed in November 1999. The results of those tests are summarized in Table 2. Figure 11 shows the slug test results by strata on a map of the model domain. Additional tests at borings FA12, FA15 and FB12 are not shown in Figure 11 as they are outside the model domain to the north. The estimated hydraulic conductivities are highly variable within each unit due to natural heterogeneity of aquifer materials. The hydraulic conductivities of the stratified sand deposits are however consistently greater than that of the clay. The geometric mean of the stratified sand hydraulic conductivities is 66 ft/day, more than 2,000 times greater than the 0.026 ft/day geometric mean of the clay hydraulic conductivity estimates. The simulated hydraulic conductivities were initially set to the geometric mean of the estimated values, however these values were modified during calibration.

Anisotropy of the hydraulic conductivity increases with increasing heterogeneity of hydraulic properties and with increasing lateral persistence of stratified systems. The stratified deposits were assigned an anisotropy ratio (vertical to horizontal hydraulic conductivity) of 4. The relatively unstratified artificial deposits were assigned an anisotropy ratio of 2 and the clay strata was assumed to be isotropic. The final calibration hydraulic conductivity values are shown in Table 3.

The specific yield of each soil material was set to a value considered to be reasonable for the soil description. Since the majority of the flow volume through the CDF occurs after the model has reached steady state the flow volume will not be sensitive to the specific yield.

Initially, during the calibration process, the simulated clay hydraulic conductivity was increased from the geometric mean in order to obtain a good estimate of the near-shore heads. Improvement of the on-shore simulated piezometric head was accomplished through reduction of the simulated stratified sand hydraulic conductivity.

Table 2 lists the residual head (measured head minus simulated head) at each monitoring well and the residual head statistics. The mean and standard deviation of the residual head is 0.03 ft and 1.2 ft respectively. Figures 12 and 13 show contours of the simulated head in the stratified sand deposits (Layer 6) and the water table elevation. Figure 12 also shows the residual head at each monitoring well.

Blue circles indicate wells with positive residual (measured head > simulated head), while red circles indicate wells with negative residuals (simulated head > measured head). In general, the near-shore residual error is less than ½ foot. Near-shore monitoring wells, MW-4A and MW-5 are the exception with residual error of nearly 3 feet. These wells were reportedly installed in soils that have likely subsided since they were originally surveyed. To the north of the proposed CDF-C, the model appears to be slightly biased with simulated heads exceeding measured heads by ½ to ¾ feet. The residual error of onshore wells nearer to the CDF-C vary between −1.99 feet and +1.16 feet. This variability in the residual may be a combination of the impacts of local heterogeneity, measurement errors and unrepresented seasonal effects.

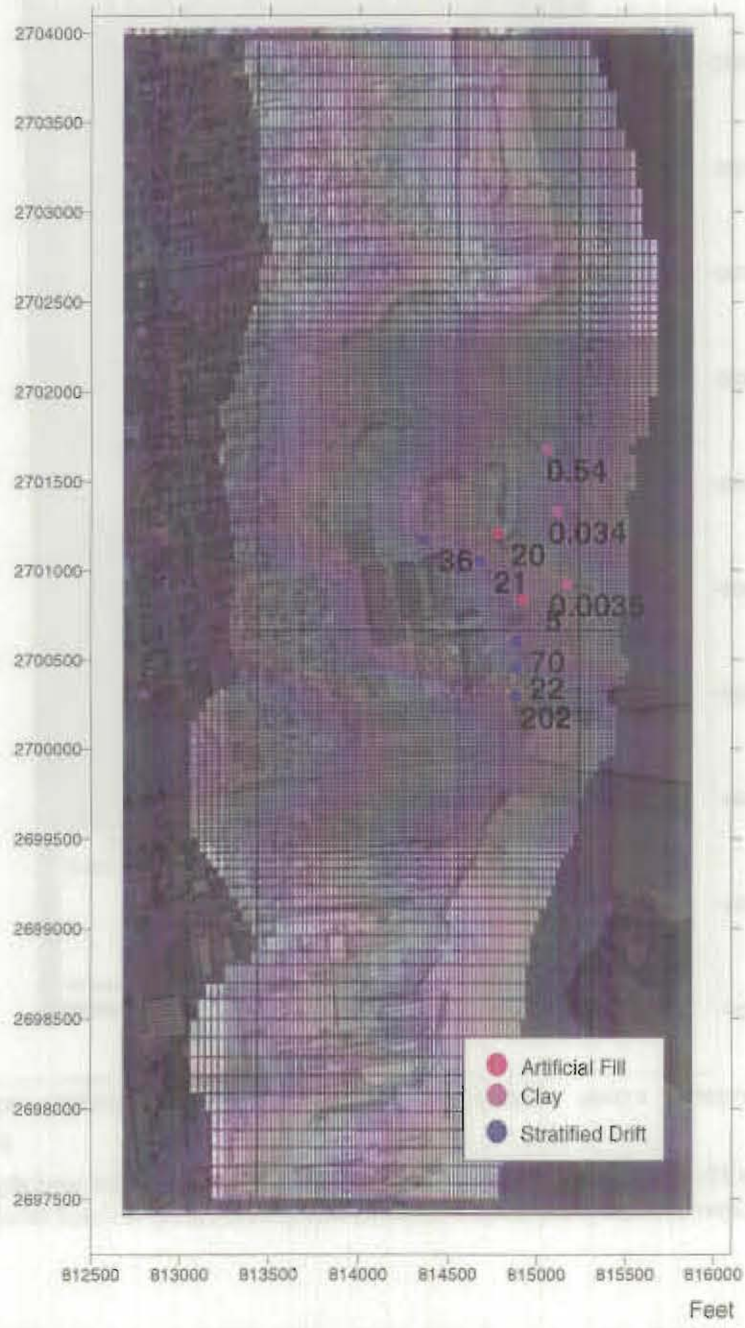


Figure 11. Location of slug tests and estimated hydraulic conductivity (ft/day) by strata.

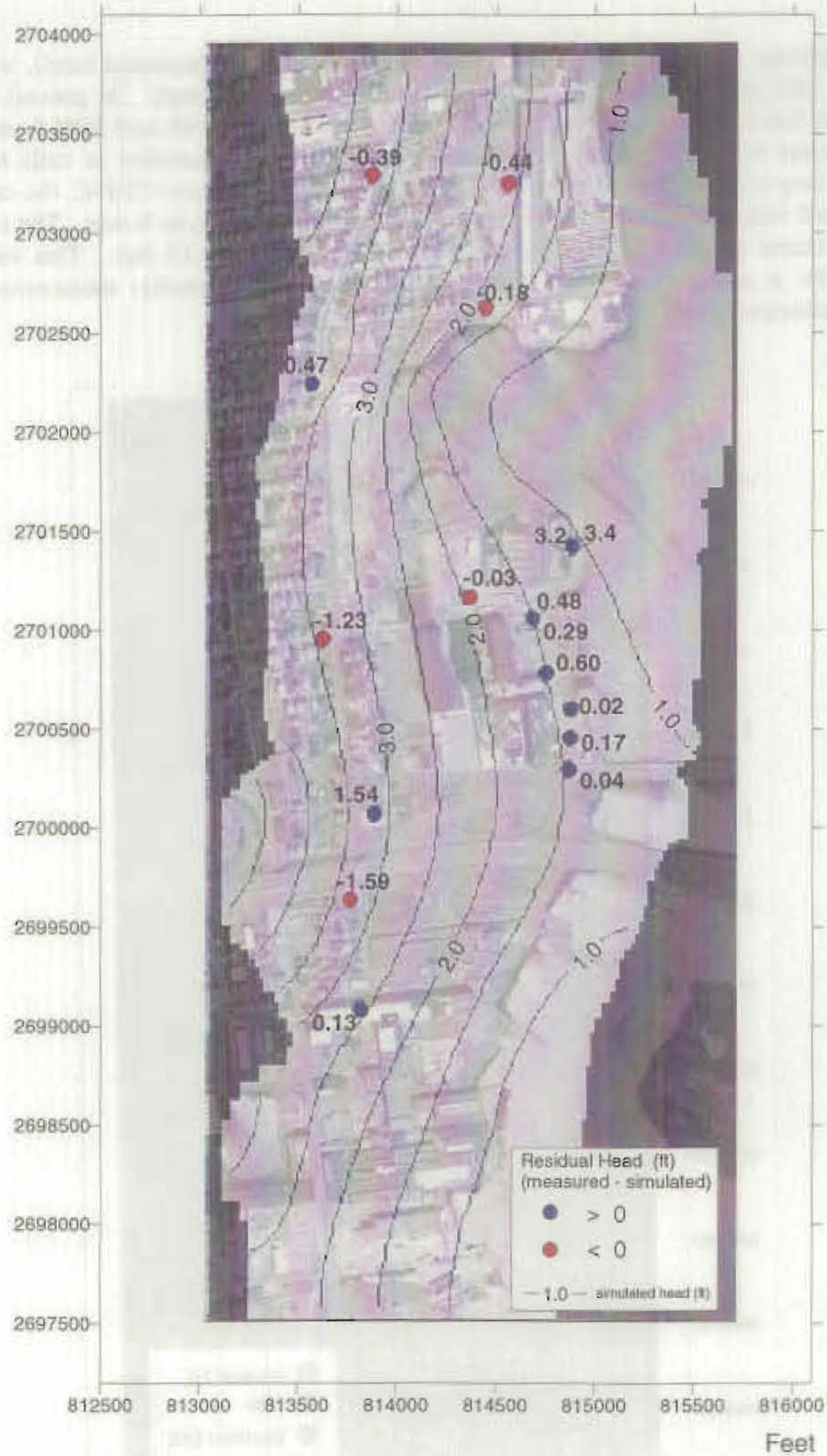


Figure 12. Contours of simulated piezometric head (ft) in stratified sand deposits (Layer 6) under calibration conditions and symbol plot of residual head.

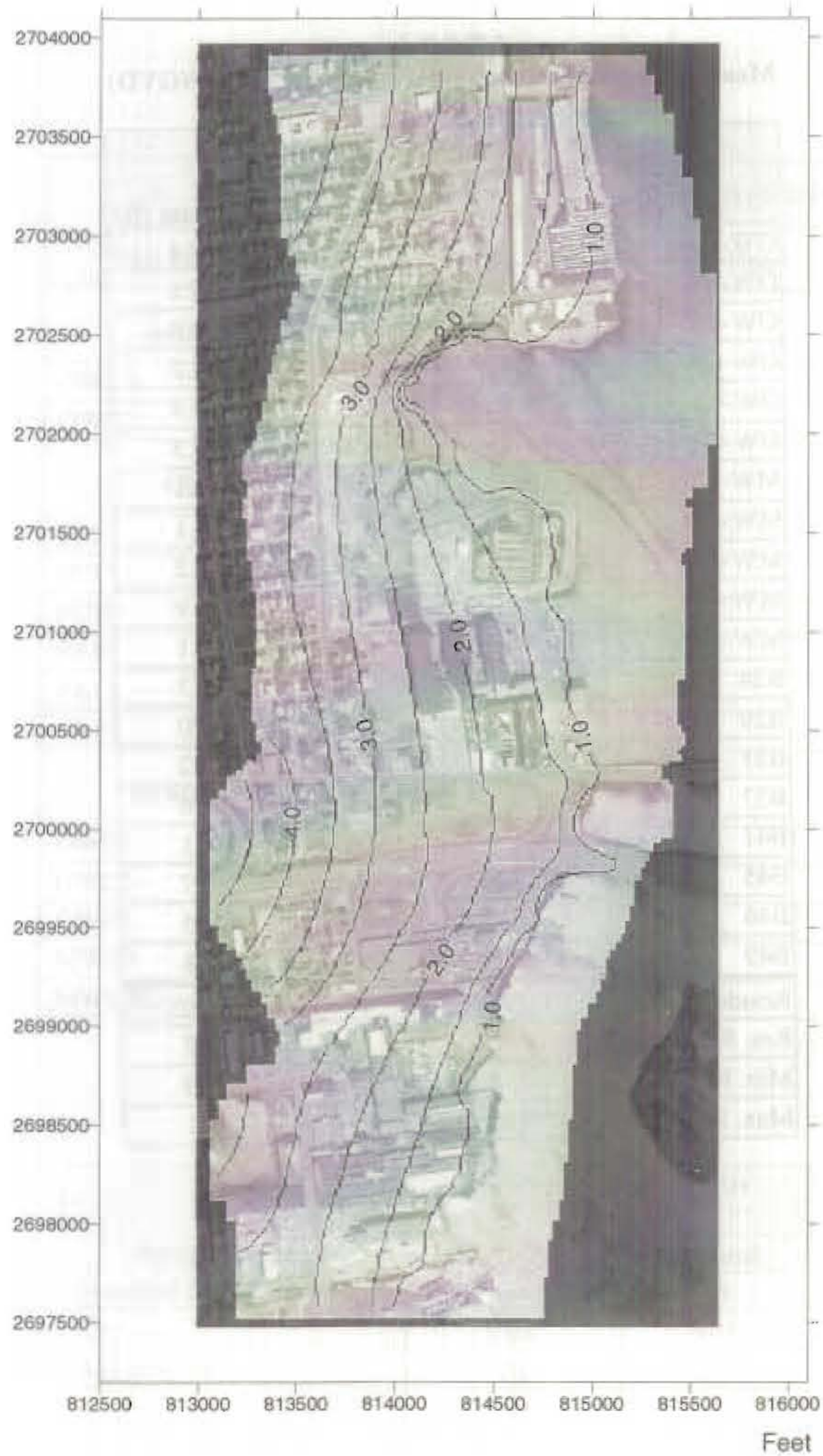


Figure 13. Contours of simulated water table under calibration conditions.

Table 4
Simulated Hydraulic Conductivity of CDF Wall Components

Component	Hydraulic Conductivity (ft/day)	Thickness (feet)
Lined Scenario		
Shore Side HDPE liner	2.80×10^{-6}	0.0067
Harbor Side HDPE liner Sheet pile Cement/Bentonite	 2.80×10^{-6} 0.28 0.0028	 0.0067 0.083 2.91
Unlined Scenario		
Harbor Side	0.28	0.042

3.6.3 Summary of Results

One hundred year transient simulations were run for the lined and unlined scenarios. The time steps were increased gradually from one day at the outset of the simulations to three years near the end, so that shorter time steps corresponded to the period of most rapid head change. Figures 17 and 18 shows the cumulative flow volumes in cubic feet out of the CDF after 30 and 100 years, for each vertical and horizontal boundary for the lined and unlined scenarios, respectively. The system achieved a steady state flow within approximately a year approaching an equilibrium head and flow rate in that time. Table 5 reports the end of simulation, total outflow volumes from layers 1 and 2 for each scenario.

The unlined cumulative Layer 2 outflow is more than 200 times those of the lined scenario. In the case of the unlined flow simulations, the flows are predominantly upward through the clay liner and then out laterally through the east boundary. The liner changes the flow field significantly, with flow entering through the bottom of the CDF and then exiting through a downgradient section of the clay. The cumulative inflow in both cases exceeds the cumulative outflow. This is due to the increase of the water table elevation within the CDF from its starting point of −1.0 ft to its equilibrium value.

The simulated equilibrium head within the CDF for the lined CDF scenario is generally one-tenth to one-half foot greater than the equilibrium head in the unlined simulations. This occurs because of the greater resistance to flow between the CDF nodes and the specified head nodes in the harbor. While the liner significantly increases the resistance to flow in the sand layer within the CDF, the incremental increase in resistance to flow in the sediment strata within the CDF is minimal because of the low hydraulic conductivity of the dewatered sediment.

The Layer 1 outflow result is counter-intuitive, with the lined Layer 1 outflow exceeding that of the unlined Layer 1 outflow. One way to understand the impact of the liner construction is to consider the Darcy's law written as $q = -\frac{\Delta h}{R}$, where Δh is the head difference over some distance L and the resistivity, R is given by L/K. For flow through a sequence of soils, or horizontally through the CDFs barrier and CDF soil, the total resistivity is the sum of the resistivity of the individual components. The

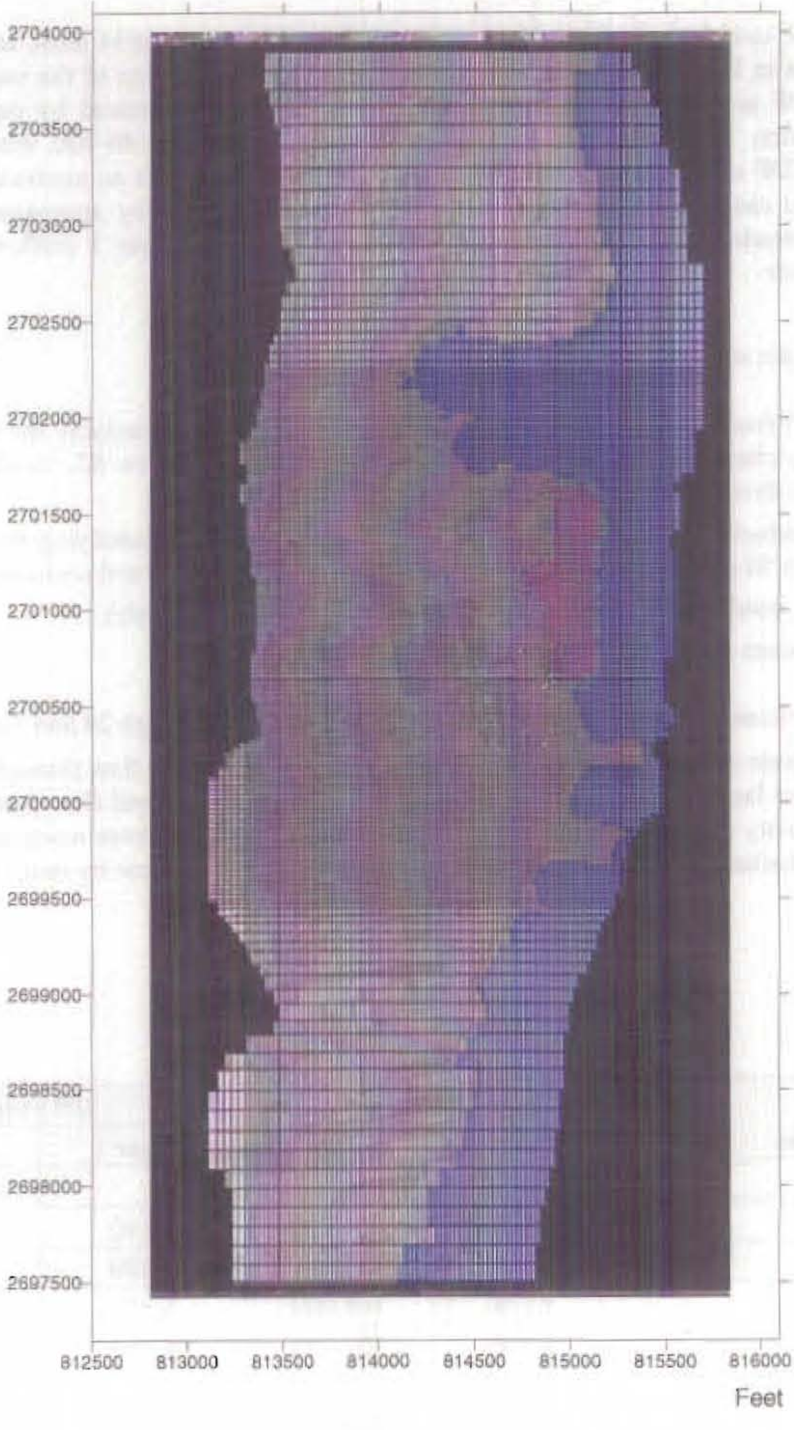


Figure 16. Specified head nodes in transient simulations – pink CDF-C nodes specified during initial one-day phase and blue river nodes specified throughout the simulation.

resistivity of the CDF unit through the sand is increased from 55 days to 6834 days, accounting for the significant reductions in flow through Layer 2 accomplished by construction of the vertical liner. The resistivity of the CDF unit through the sediment (for years 1-45) is increased by only 5 percent by construction of the liner. The difference in resistance is even less for years 46-100, where the hydraulic conductivity of the CDF sediment is reduced by an order of magnitude. For an equivalent flow field, in the lined and unlined cases, the flow through layer 1 would be reduced by approximately 5 percent, however the higher heads within the CDF in the lined case cause the Layer 1 outflow to increase on construction of the liner.

Four sensitivity analyses were performed.

1. A 100 by 100 foot area hole was introduced into the clay layer underlying the CDF. This was carried out by changing the soil property assignment for 4 nodes (row 65, column 92 – row 66, column 93) to those of the stratified deposits (lined and unlined).
2. Hydraulic conductivity was doubled for nodes in the clay strata underlying the CDF. This is equivalent to a 50 percent reduction of the clay layer thickness (lined and unlined).
3. Recharge rate inside CDF increased 100 times to 0.045 in/yr (lined only).
4. Lined wall system modified by removing eastern portion of wall.

The computed flow volumes for these cases are presented in Figures 19 through 24 and Table 5.

The introduction of a hole in the clay layer had only a marginal impact on the flow through the layer. The hole was apparently not large enough to cause significant changes in the overall flow patterns. Doubling the hydraulic conductivity of the clay layer over the whole model reduced flows marginally through the CDF. Increasing the recharge rate by 100 times increases the Layer 1 outflow by more than a factor of ten.

Table 5
Cumulative CDF-C Outflow Volumes (ft^3)

Scenario	30 years		100 years	
	Layer 1	Layer 2	Layer 1	Layer 2
Lined CDF				
Base Case	3,720	194,000	7,140	526,000
Hole in Clay	3,760	198,000	7,220	540,000
Permeable Clay	3,570	208,000	6,870	574,000
High Recharge	29,400	207,000	94,200	575,000
Unlined CDF				
Base Case	1,140	2,260,000	2,040	7,460,000
Hole in Clay	1,140	2,270,000	2,040	7,480,000
Permeable Clay	1,510	2,940,000	2,660	9,700,000
Western Liner	1,500	2,040,000	2,940	6,690,000

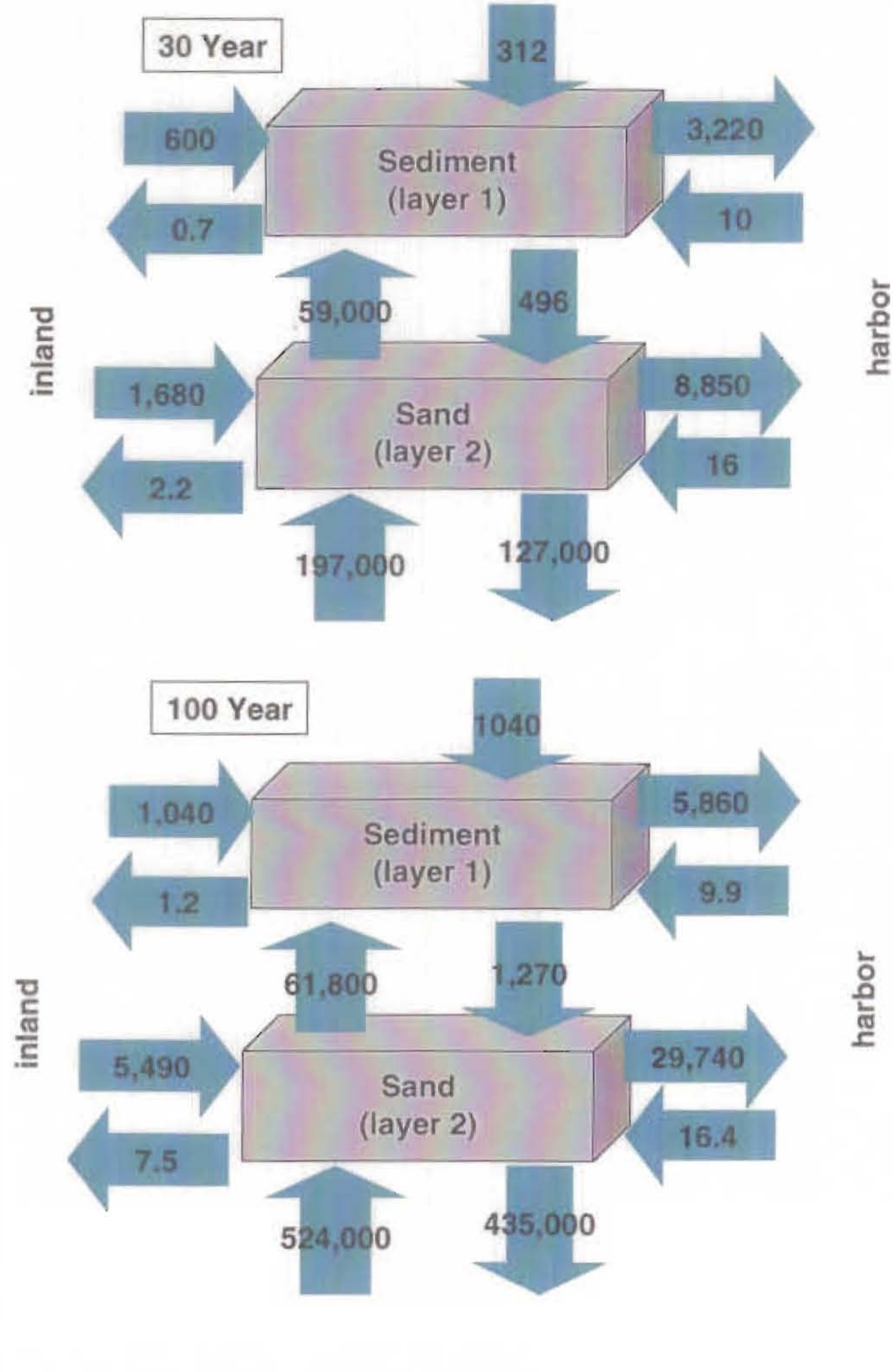


Figure 17. Estimated flow volumes (ft^3) through lined, base-case CDF-C over 30 and 100 years

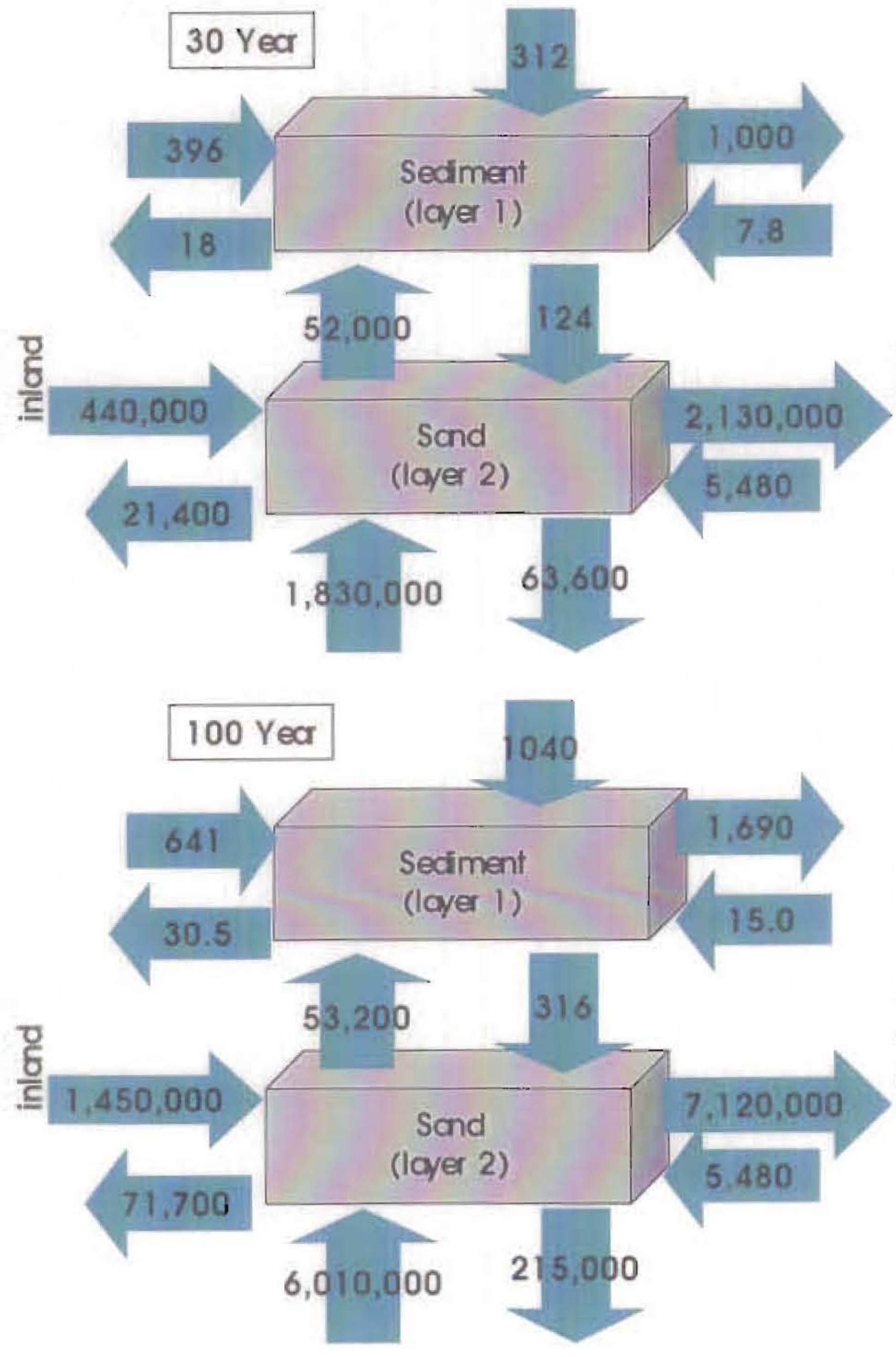


Figure 18. Estimated flow volumes (ft^3) through unlined, base-case CDF-C over 30 and 100 years.

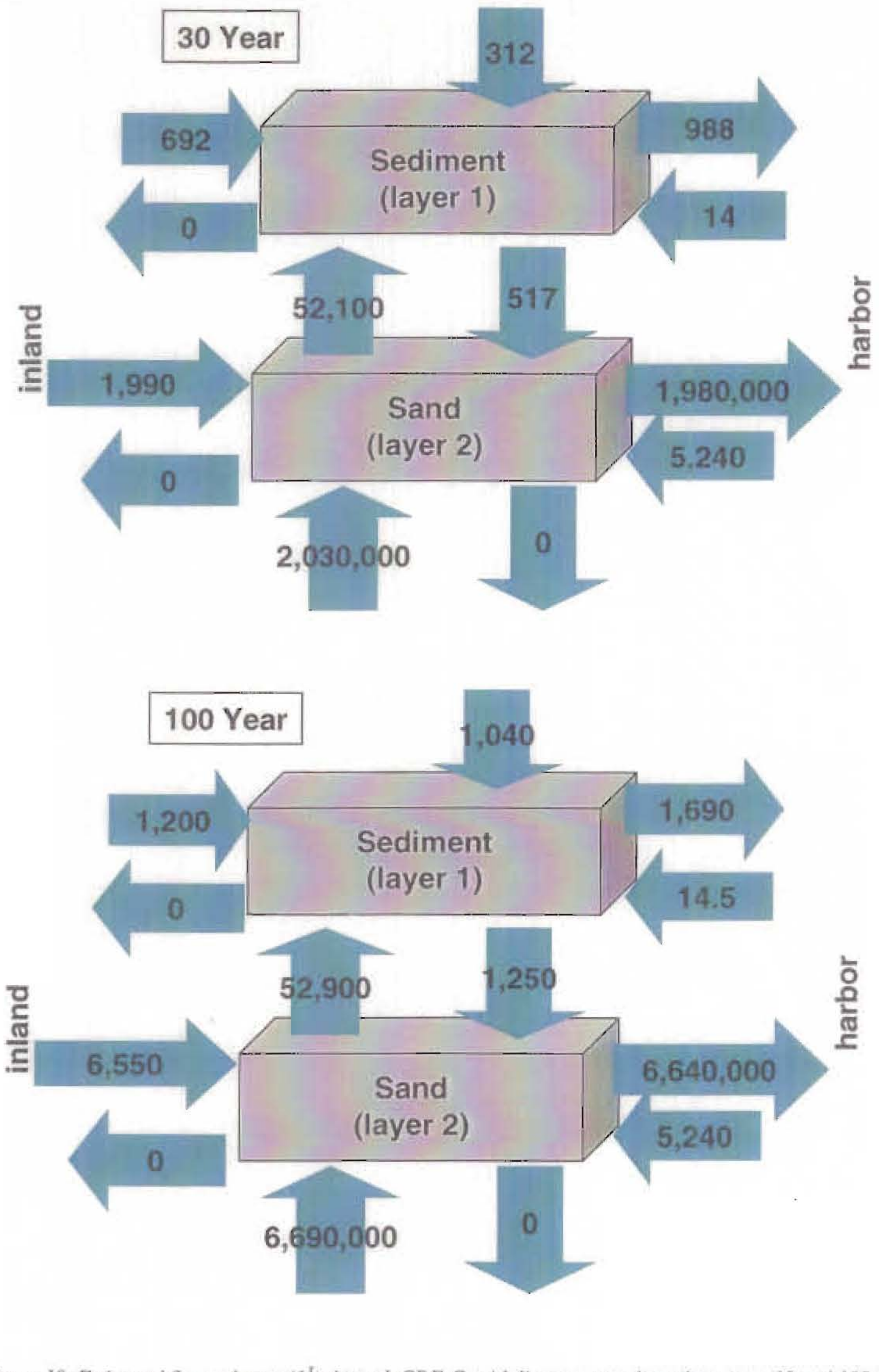


Figure 19. Estimated flow volumes (ft^3) through CDF-C, with liner on west boundary, over 30 and 100 years.

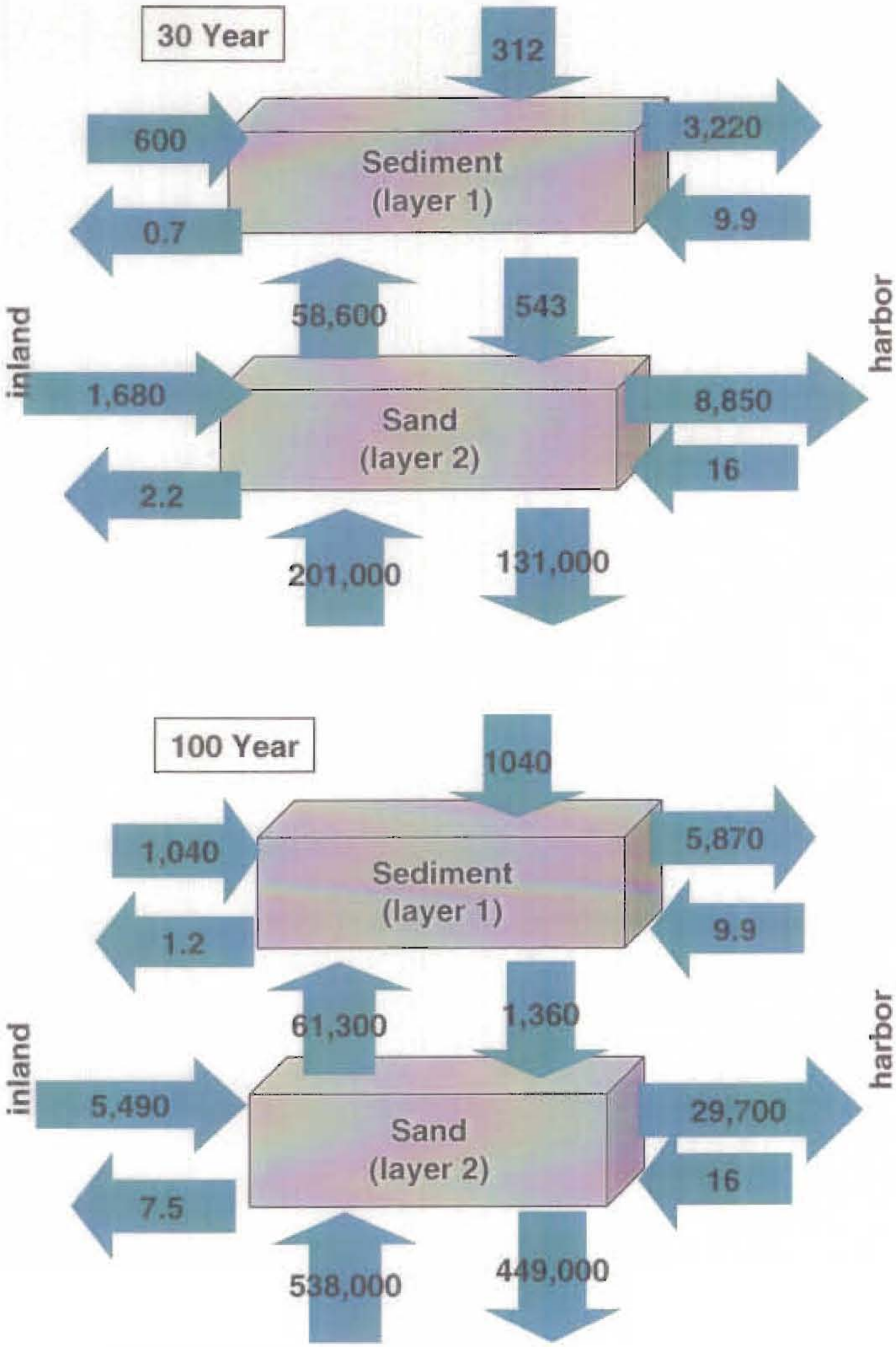


Figure 20. Estimated flow volumes (ft^3) through lined CDF-C with 100-foot by 100 foot hole over 30 and 100 years.

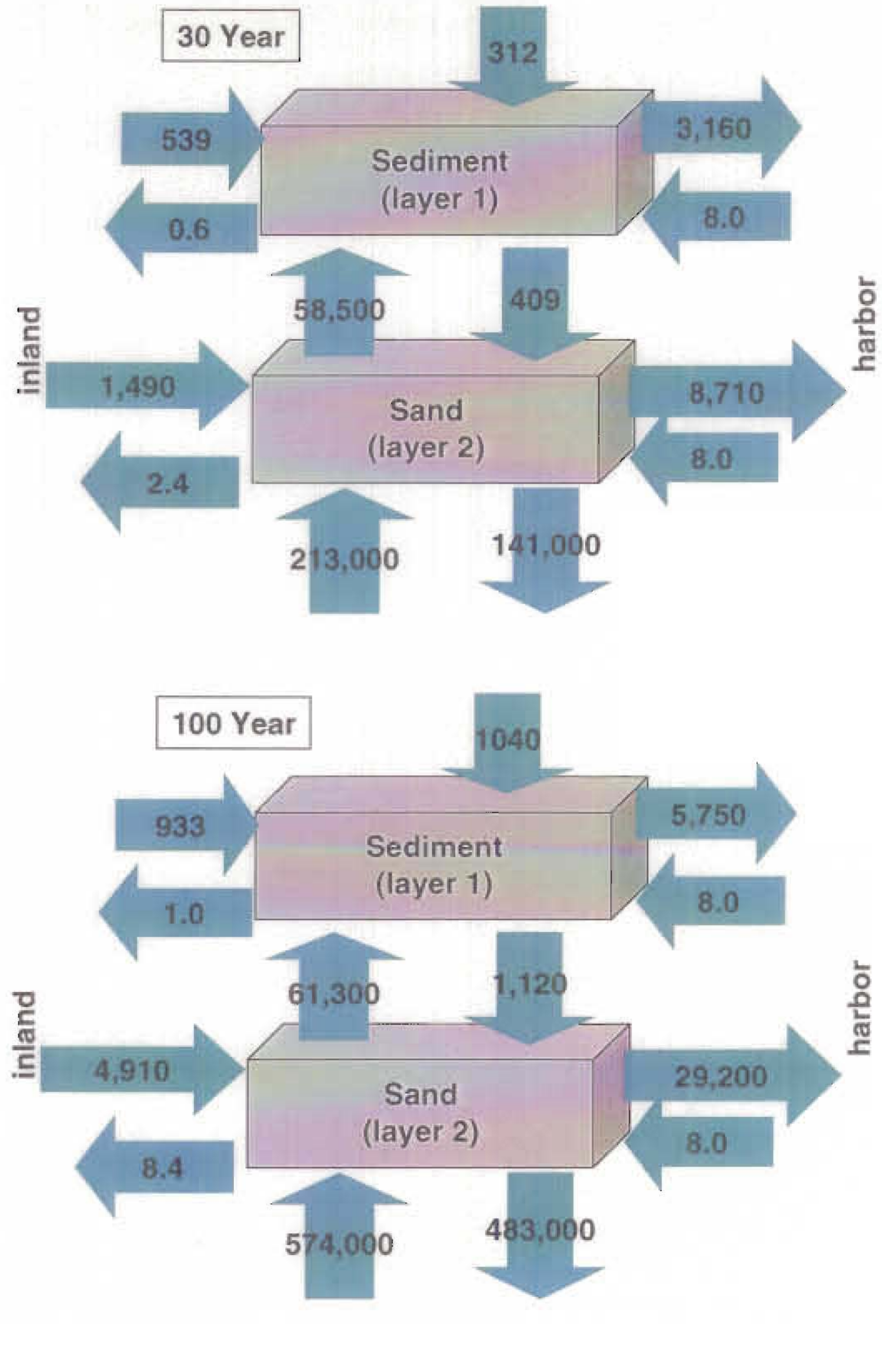


Figure 21. Estimated flow volumes (ft^3) through lined CDF-C, with hydraulic conductivity in clay underlying CDF elevated by factor of 2, over 30 and 100 years.

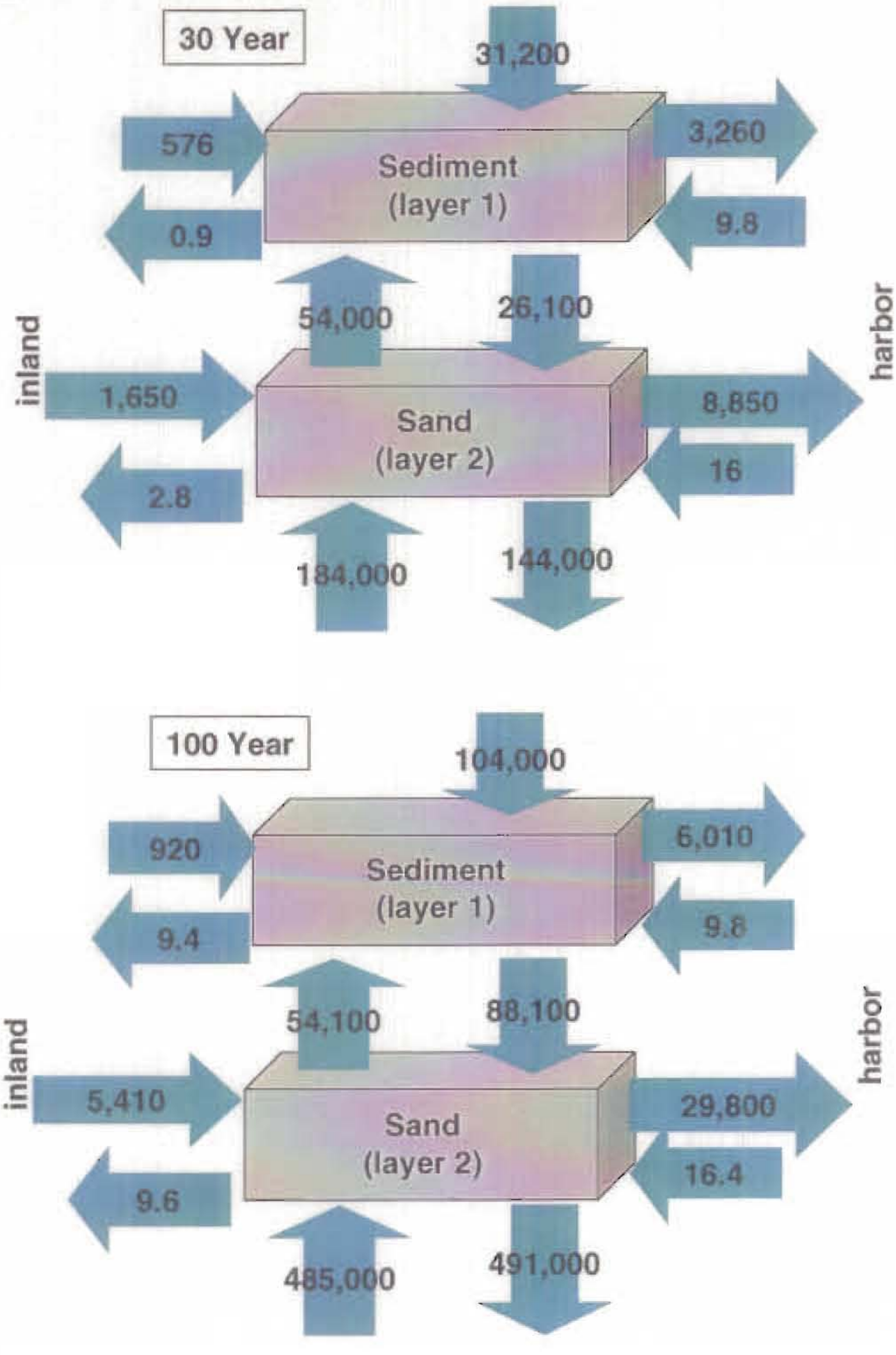


Figure 22. Estimated flow volumes (ft^3) through lined CDF-C, with CDF recharge elevated 100 times, over 30 and 100 years.

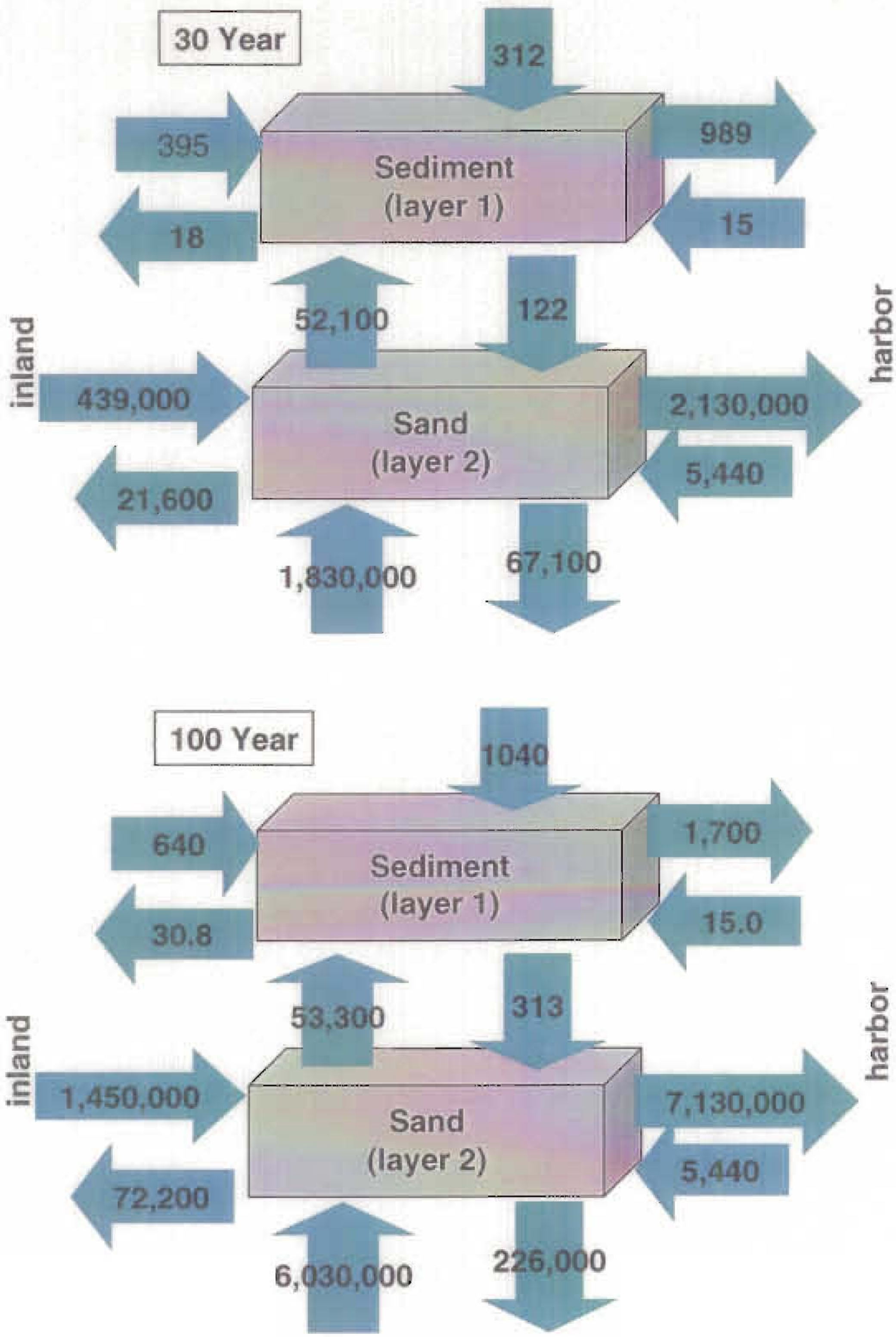


Figure 23. Estimated flow volumes (ft^3) through unlined CDF-C with 100-foot by 100 foot hole over 30 and 100 years.

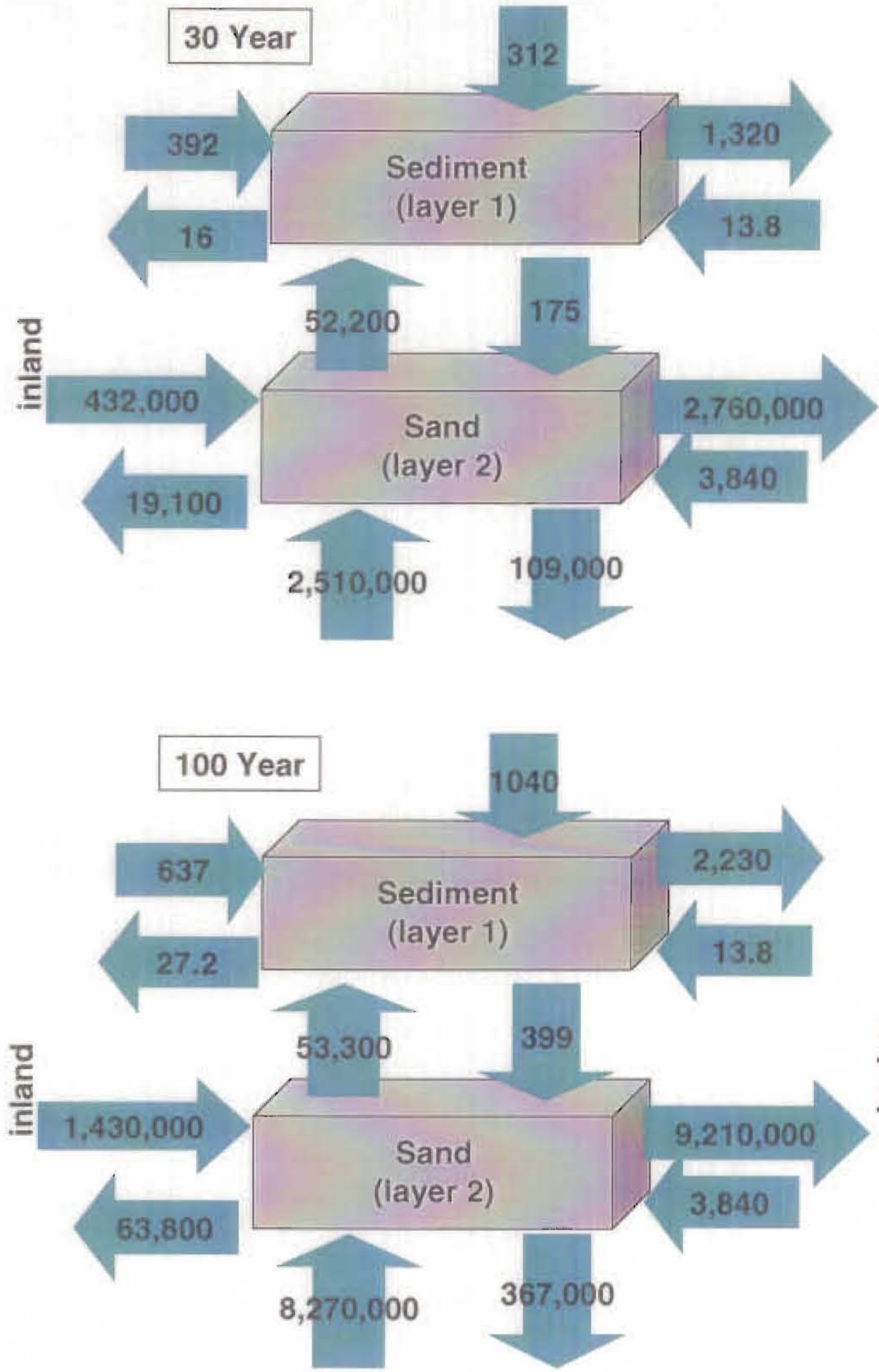


Figure 24. Estimated flow volumes (ft^3) through unlined CDF-C, with hydraulic conductivity in clay underlying CDF elevated by factor of 2, over 30 and 100 years.

4.0 TIDAL MODEL

The tidal model was constructed to enable comparison of flows generated by tidal variability in the lined and unlined scenarios and flows generated by regional gradients. The transmission of the tidal signal is frequently observed in coastal aquifers. Tidal variability appears as a periodic signal lagging behind the rise and fall of surface water, with an amplitude that diminishes with inland distance. In aquifers that may be approximated as one-dimensional and homogeneous, the amplitude diminishes in proportion to $\exp\left(-x\sqrt{S/T}\right)$, where x is the inland distance, T is the aquifer transmissivity and S is the storage coefficient. Therefore transmission of the tidal signal is most intense for highly transmissive aquifers with small storage coefficients. Confined materials are ideal for transmission of the tidal signal as the storage coefficient values are several orders of magnitude less than most unconfined materials.

4.1 Discretization of Model Domain

A two-dimensional vertical model was used for analysis of tidal flows. The model is aligned in the east-west direction with the east boundary in the harbor and the west boundary coincident with the western extent of the CDF. The harbor boundary is assumed to be 20 feet east of the CDF, while the interior of the CDF extends 265 feet to the west. Figures 25 and 26 show the model geometry, layer numbers, boundary conditions and material assignments of the tidal model for both the lined and unlined scenarios. Model nodes are 1 foot in width at the boundaries and reduce to ¼-foot through the liner and in the region immediately to the west within the CDF.

The bottom of the model is at –4 feet. From the bottom up, within the CDF-C, the model consists of a 3 foot thick sand strata (Layers 4 and 5) and an additional 4 feet of sediment (Layers 1, 2 and 3). The embankment on the harbor side of the CDF-C extends over the full 5-layer thickness. The sheet pile wall and HDPE liner in the lined scenarios are treated using MODFLOW's horizontal flow barrier package, as were the liner walls in the long term model. The three-foot thick barrier wall in the CDF liner is treated explicitly using nodes of ¼-foot width.

The area east of the CDF represents the CDF embankment. The hydraulic conductivity has been set to 50 ft/day, consistent with a medium to coarse sand. The horizontal and vertical hydraulic conductivity in the sand underlying the sediment (Layers 1 and 2) are set at 3 ft/day and 5 ft/day as in the long-term model. The sediment layers are set at 3×10^{-3} ft/day, the value used in the long term model for the dewatered sediment at the outset of the simulations.

All boundary nodes were assigned a no-flow condition with the exception of the harbor side boundary. The harbor side boundary was assigned a time varying specified head condition, varying as a sinusoidal curve between –0.6 and 3.0 feet, with a period of 12.75 hours.

4.2 Summary of Results

The tidal models were run for 60 days to eliminate transients associated with the starting conditions. Time histories of the piezometric head at the eastern model boundary and at various points within the model are shown in Figures 27 and 28 for the lined and unlined scenarios. In the lined scenario, the heads within the CDF are not visibly affected at a distance of 10 feet from the barrier. The heads in the upper sediment layer of the unlined scenario are also not visibly affected, however in the lower sand deposits the tidal signal is visible, with the heads varying between 0.5 and 2.0 feet. The lower sand deposits in this unlined scenario are acting as a confined aquifer. As explained above, the relatively high transmissivity of the sand strata and low storage coefficient of a confined aquifer are conducive to the propagation of the tidal signal through an aquifer unit.

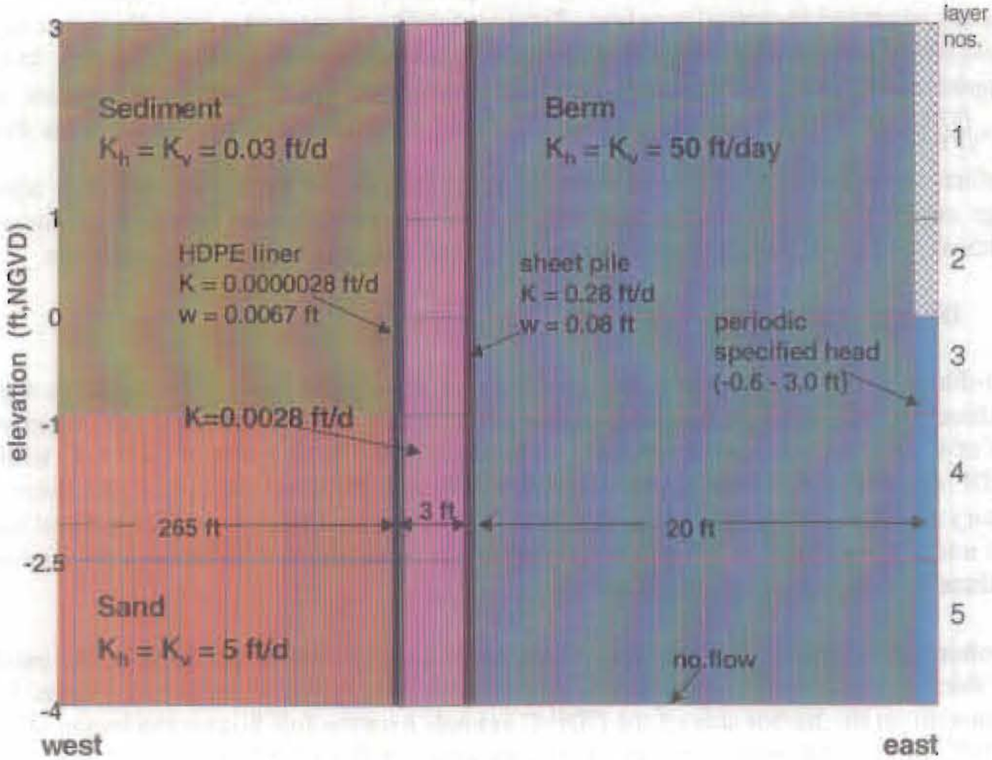


Figure 25. Modeled stratigraphy of tidal model of lined CDF-C.

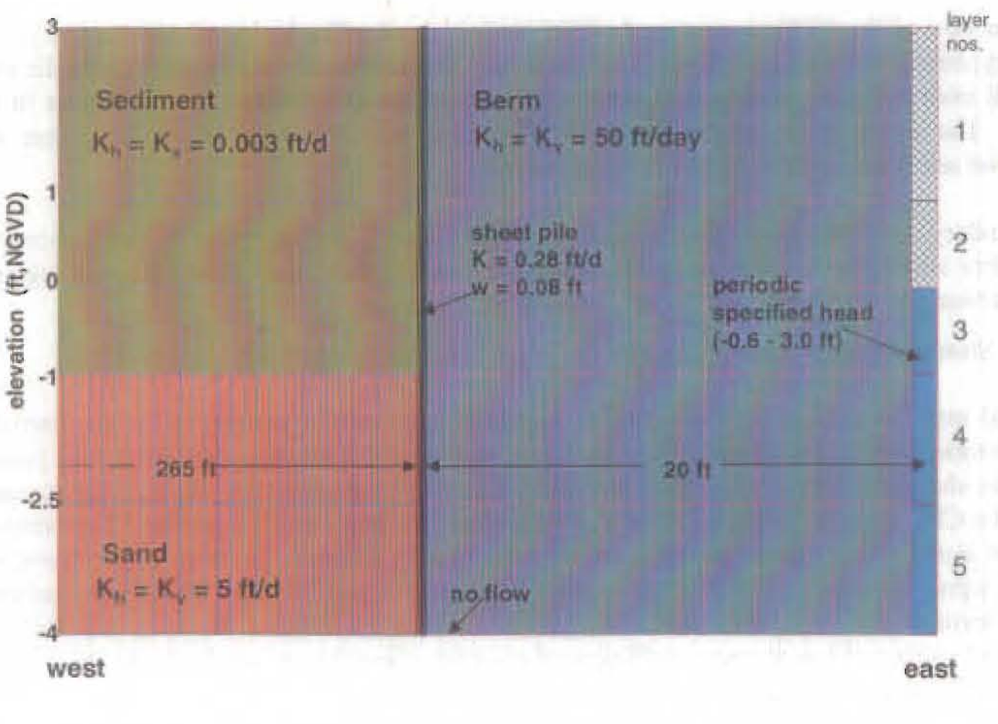


Figure 26. Modeled stratigraphy of tidal model of unlined CDF-C.

The flows through the CDF barrier and between the sediment (layer 3) and sand (layer 4) within the CDF were estimated using GW Vistas to process the MODFLOW generated output files and plotted for each layer over a single tidal period (see Figures 29 and 30). The flows in the unlined case are on the order of 100 times those of the lined case. An average outward daily flow through the CDF was estimated based on the tabulated results. The average daily outflow for the unlined case was 0.10 cubic-feet/day per linear foot of the CDF perimeter, while the average flow for the lined case was 0.00023 cubic feet/day per linear foot. Based on a CDF-C perimeter of 1,476 feet, the 100-year outflow is 1.2×10^4 ft.^{3} for the lined CDF-C and 5.5×10^6 ft.^{3} for the unlined CDF-C.

The tidally driven groundwater flows in the sand strata within the CDF cause water to be pumped in and out of the overlying sediment. This is not a significant effect for the lined case, with 0.00013 ft^3/day per linear foot of the CDF perimeter, however the impact is far greater in the unlined case with a daily rate of flow of 0.073 ft^3/day per linear foot of the CDF perimeter. For a CDF perimeter of 1476 ft, this would signify 3.9 million cubic feet of water over 100 years for the unlined case and 7000 cubic feet over the same period for the lined case.

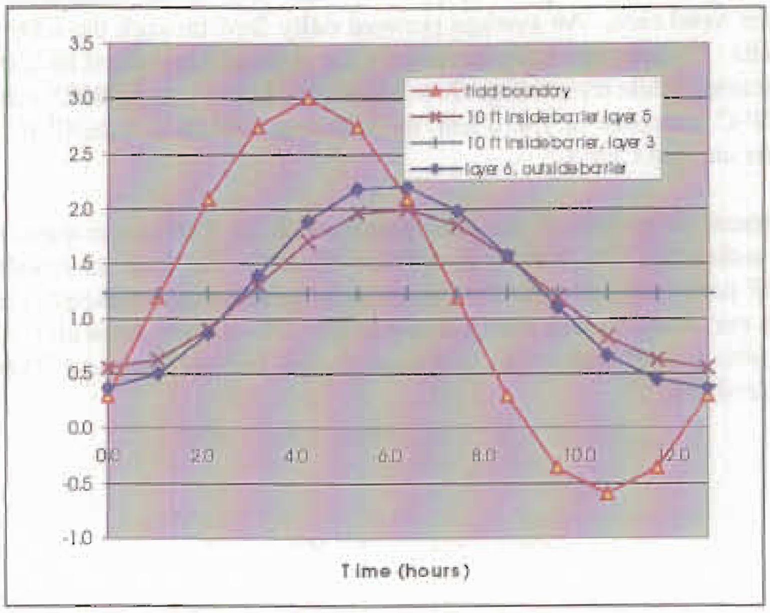


Figure 27. Simulated Piezometric head at selected points inside and outside of the barrier for the lined CDF-C tidal model simulation.

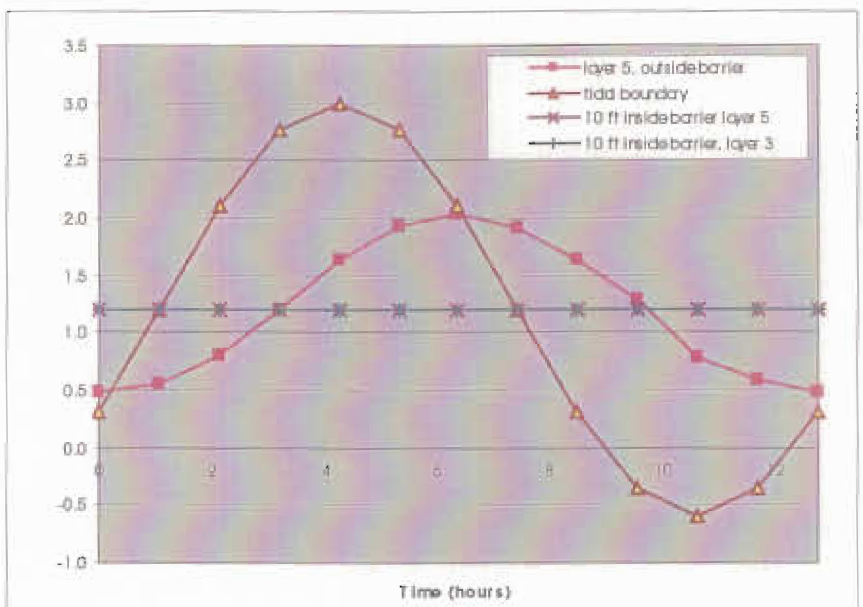
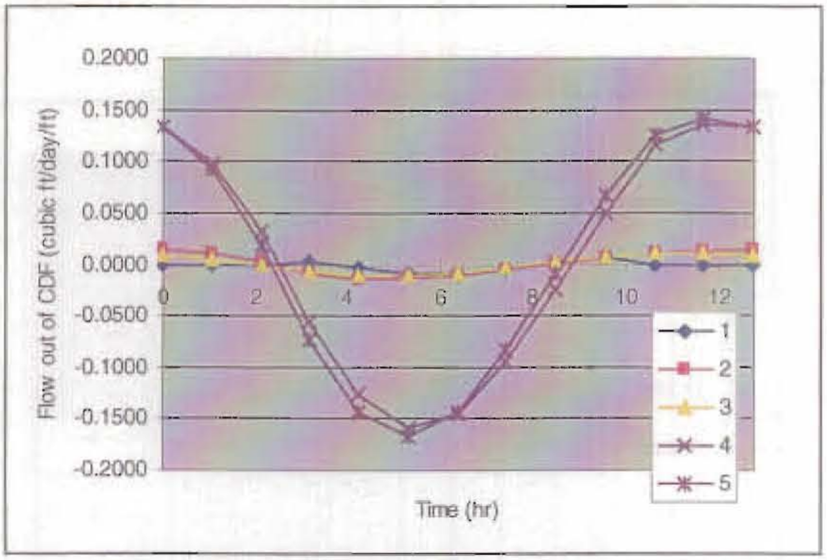


Figure 28. Simulated Piezometric head at selected points inside and outside of the barrier for the unlined CDF-C tidal model simulation.



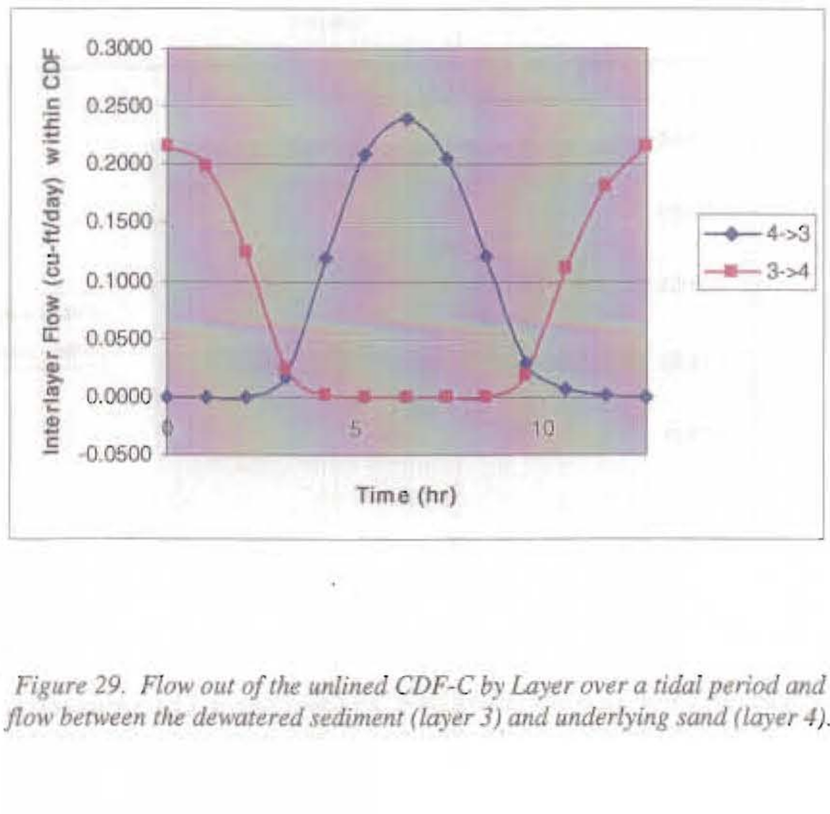


Figure 29. Flow out of the unlined CDF-C by Layer over a tidal period and flow between the dewatered sediment (layer 3) and underlying sand (layer 4).

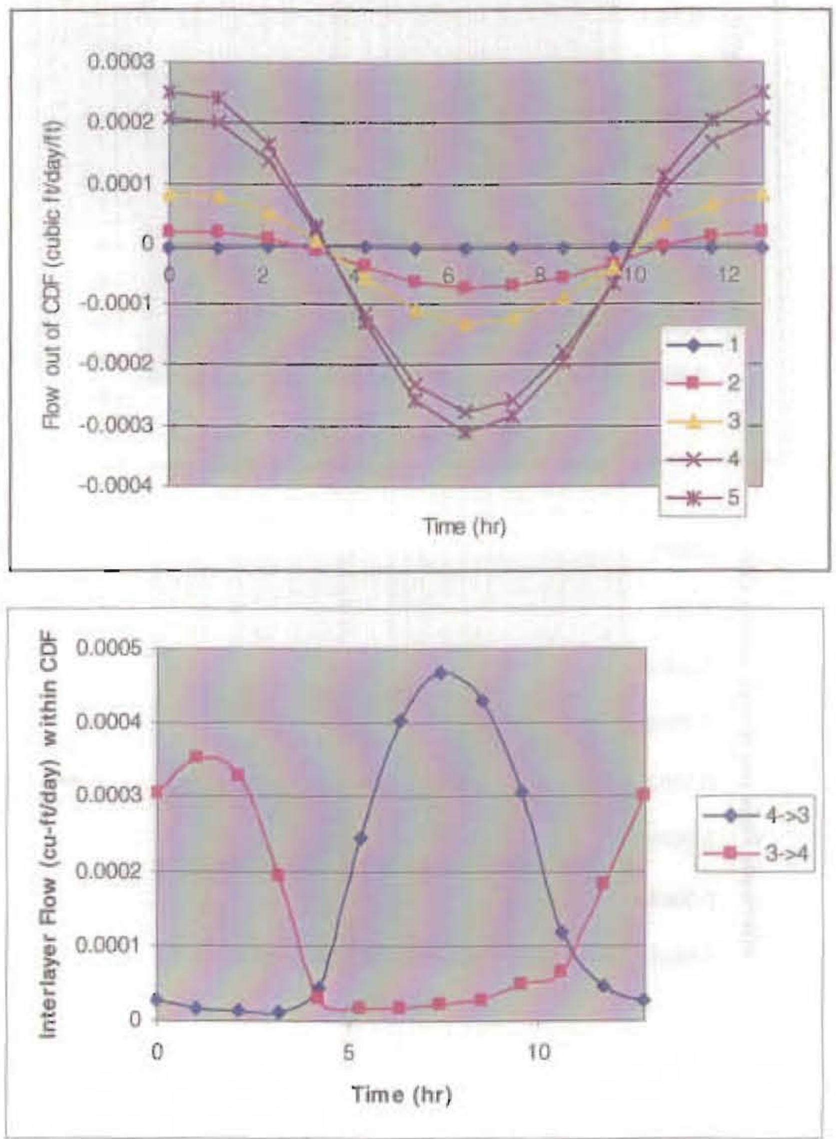


Figure 30. Flow out of the lined CDF-C by Layer over a tidal period and flow between the dewatered sediment (layer 3) and underlying sand (layer 4).

5.0 SUMMARY OF ESTIMATES EVALUATING PCB LOSSES FROM CDF C

5.1 Introduction

The following section presents the application of PCB Pore water concentrations to the groundwater flows estimated for the current design of Confined Disposal Facility C (CDF C).

a) Section 5.2 summarizes previous PCB loss estimates specified in the OU#1 Record of Decision (ROD), dated September 1998.
b) Sections 5.3 through 5.5 present the PCB loss estimates based on groundwater modeling.

5.2 USACE Waterways Experiment Station PCB Loss Estimates

In a technical memo (FWENC 2000a) submitted in October 2000, Foster Wheeler reviewed previous PCB loss estimates conducted by the United States Army Corps of Engineers Waterways Experiment Station (WES). The review of existing PCB loss estimates was conducted in conjunction with the evaluation of alternative contaminant barrier systems for the current design and construction of Confined Disposal Facility C (CDF C).

5.2.1 WES PCB Loss Estimates

PCB losses estimated from the final round of contaminant loss evaluation by WES are reported in Table 6.0. The estimate is based on assumed hydrogeologic conditions, hydraulically placed sediment and PCB loss solely via advective groundwater transport. For CDF C, the WES evaluation estimated a PCB loss of 7.8 kg of PCB's over 30 years and 9.0 kg over 100 years. These estimates were incorporated into the Record of Decision which limit total losses from all CDF's to 37 kg.

The review of the existing PCB loss estimates suggested the following:

a) Continue to incorporate changes in the CDF design and construction into the leachate loss estimates.
b) Define groundwater flow through CDF C, previously assumed by WES by incorporating the current CDF C design and using new site specific information.
c) Evaluate new PCB losses using the above and compare to those stated in the ROD.

5.3 Groundwater Modeling and PCB Loss Estimates from Dewatered Material Overlying 3 Foot Sand Foundation Layer

The following section presents the PCB loss estimates from CDF C using the groundwater flows reported in Sections 3.0 and 4.0. Analogous to the WES loss estimates, the following PCB losses are estimated directly by associating a pore water concentration of PCB with the groundwater flow determined from the modeling.

A PCB pore water concentration of 0.266 mg/L was used to estimate the loss of PCB from the CDF. This concentration corresponds to the pore water concentration used in the previous PCB loss estimates completed by the WES. The pore water concentration was selected based on batch leaching tests conducted on composite samples of the harbor sediments. The composite sample was prepared to represent a hydraulically dredged/placed material, commonly referred to as the *composite upper estuary sample* at a 4:1 water to sediment ratio. The PCB sediment concentration used throughout the WES batch leaching tests represented the midrange (in 1989) of PCB concentration in the upper estuary portion of the Acushnet River (an approximate PCB sediment concentration of 1500-2150 mg/kg). Further details are provided in Report 3 - Leachate Characterization contained in the series of WES Feasibility Studies. A large range of PCB concentrations were observed for the batch tests conducted on the composite sediment sample under aerobic/anaerobic and saline/fresh water conditions (0.14 to 4.4 mg/L). Preliminary tests conducted on the dewatered sediment have reported higher sediment concentrations than the composite sample used to prepare the hydraulic sample (4000 mg/kg). The explanation for this may be attributed to the dewatering process itself or perhaps to the variability of the harbor sediment. In either case it provides some uncertainty regarding the use of 0.266 mg/L in the PCB loss estimates. In addition it should be noted that the current scenario for the filling of CDF-C is that the dewatered cake will be placed with very little compactive effort (i.e. just the dozer load passing over the sediment during placement). This will likely leave the in place dewatered sediment with voids, and potentially a higher permeability than used in the modeling, and thus a greater potential for groundwater flow through the sediment. Hence consideration of the method of placement may also influence the pore water concentrations. By using an assumed constant porewater concentration, the mass loss of PCB is directly proportional to the volume of contaminated water that moves through the CDF

5.3.1 PCB Loss Estimates

Figures 31 and 32 present schematic diagrams of the groundwater flow within the CDF and at the CDF boundaries. The net groundwater flows out of each soil or sediment layer are summarized in Table 5 and shown in detail in Figures 17 through 24. The groundwater flow exiting the boundaries of the dewatered sediment results in low groundwater flow volumes (see Figure 18). The presence of the 3 ft sand layer underlying the contaminated dewatered sediment may imply a preferential pathway for PCB losses. Large horizontal volumetric flows are reported in the 3 ft sand layer, but the groundwater modeling suggests that little groundwater is transmitted vertically to the sand layer, which results in the low estimates of PCB losses. Table 7 reports the ground water volumes and the estimated PCB loss from the dewatered sediment (layer 1) for the scenarios evaluated groundwater modeling effort. For the base case dewataered placed sediment, in an unlined CDF, the estimated PCB loss was approximately 0.009 kg over 30 years and 0.02 kg over 100 years. For base case dewatered placed sediment , in a lined CDF, the estimated PCB loss was approximately 0.03 kg over 30 years and 0.05 kg over 100 years. The loss form the lined case is slightly greater than from the unlined case because there is greater net flow from the dewatered sediment in the lined case (as explained in Section 3.6.3). The estimate does not account for contamination migration by diffusion from the dewatered sediment into the sand layer at the interface between the sediment and the sand. This process would add to the PCB losses from the dewatered sediment. Conversely, effects of sorption of PCBs to materials after leaving the dewatered sediment could reduce PCB losses from the CDF boundaries. A more significant impact of the sand layer presence is presented when considering the groundwater losses from the tidal impact.

5.4 Tidal Influence on Groundwater Flow and PCB Loss Estimates from Dewatered Sediment

A separate groundwater model was developed to evaluate the influence of tidal fluctuations on the groundwater exiting along the eastern boundary for an unlined and lined CDF. Table 8.0 presents the groundwater flux across the eastern boundary due to tidal fluctuations, along with the estimated PCB loss associated with the contaminated pore water from the CDF. Again the contaminant loss is assumed to occur via advective groundwater transport, and the pore water concentration based on the batch leaching tests conducted on hydraulically placed dredged sediment of 0.266 mg/L. For dewatered placed sediment in an unlined CDF the estimated PCB loss was 9 kg over 30 years and 11 kg over 100 years. For dewatered placed sediment in a lined CDF the estimated PCB loss was 0.02 kg over 30 years and 0.05 kg over 100 years.

5.5 Summary

The current groundwater modeling and tidal simulation have been conducted to characterize the flow of groundwater surrounding CDF C and to estimate the mass of PCB exiting the boundaries of the CDF. For this report, and previous reports by WES, the loss of PCB's from the CDF is assumed to be associated directly with the outward groundwater flow from the dewatered material, that is the concentration of PCB in the pore water contained in the dredged material is transported solely by the groundwater movement. The pore water concentration is based on batch leaching tests conducted by WES which represent a hydraulically placed dredged sediment with a PCB sediment concentration of 2,150 mg/kg under anaerobic testing conditions, and 1,500 mg/kg under aerobic conditions. The use of the PCB pore water concentrations from the batch leaching tests, although not uniquely specific to the dewatered sediment placement method, may be seen to be conservative when considering that the column leaching tests conducted on the same sample were of an order of magnitude lower. If warranted further column tests could be conducted on dewatered sediment to confirm that the PCB pore water concentration will not exceed those reported by the batch leaching tests.

From Section 5.3.1 groundwater transport of PCB contaminated pore water suggested that the mass of PCB exiting the dewatered sediment would not exceed the level reported in the ROD. From Section 5.4 the tidal simulation suggests that the mass loss of PCB existing the CDF will exceed the maximum requirements stated in the ROD.

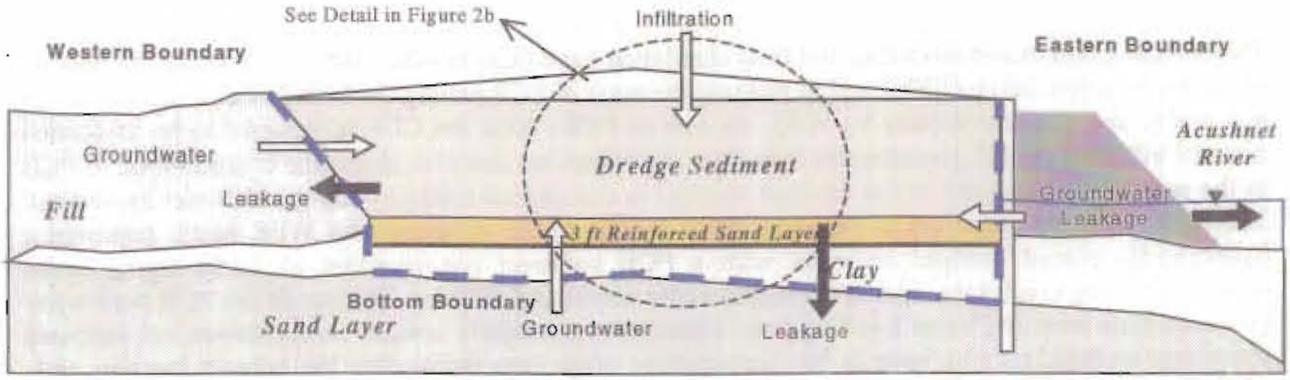


Figure 31 - Schematic of CDF Boundaries

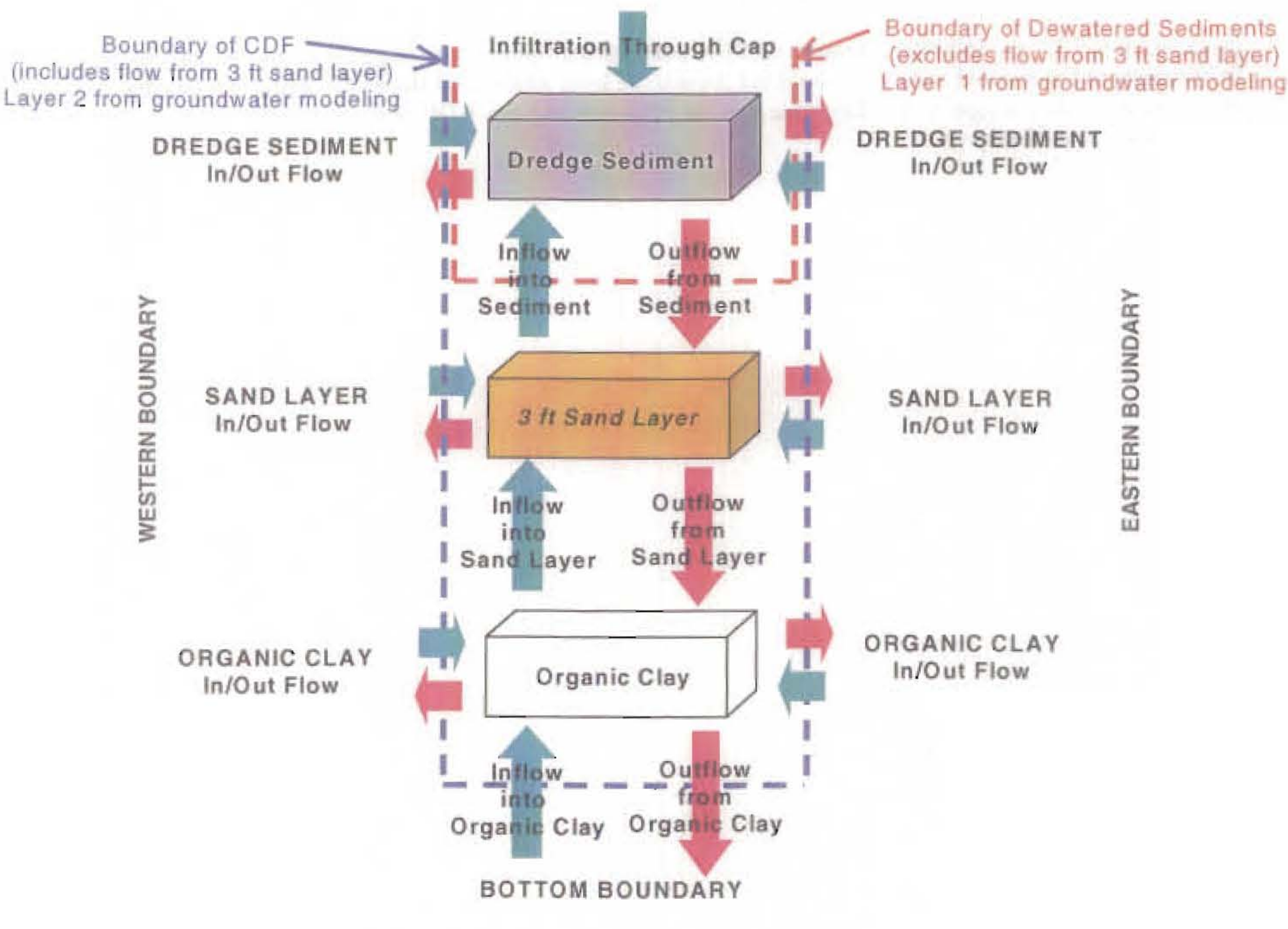


Figure 32 - Flow within CDF Boundaries

Table 6
WES PCB Loss Estimates from CDF-C

USACE Waterways Experiment Station PCB Loss Estimates

Sediment Placement	Time (yrs)	PCB Concentration C_o(TPCB) (mg/L)	Total Groundwater Flow HELP Modeling	Total PCB Loss Advective Loss (kg)
Hydraulic Placed Sediment	30	0.3	1,138,347	7.8
Hydraulic Placed Sediment	100	0.3	400,822	9.0

Note : Dewatered Porewater Concentrations Based on Batch Leaching Tests Representative of Hydraulic Placed Sediments

Table 7
Groundwater Flux and Estimated PCB Loss from CDF-C

	Scenario	30 years Volume of Flow (cu-ft) Layer 1 [B]	PCB Loss (kg) [A] Layer 1 [B]
Lined CDF	Base Case	3,720	0.03
	Hole in Clay	3,760	0.03
	Permeable Clay	3,570	0.03
	High Recharge	29,400	0.22
Unlined CDF	Base Case	1,140	0.009
	Hole in Clay	1,140	0.009
	Permeable Clay	1,510	0.01
	Western Liner	1,500	0.01
	Scenario	**100 years Volume of Flow (cu-ft) Layer 1 [B]**	**PCB Loss (kg) [A] Layer 1 [B]**
Lined CDF	Base Case	7,140	0.05
	Hole in Clay	7,220	0.05
	Permeable Clay	6,870	0.05
	High Recharge	94,200	0.7
Unlined CDF	Base Case	2,040	0.02
	Hole in Clay	2,040	0.02
	Permeable Clay	2,660	0.02
	Western Liner	2,940	0.02

[A] - PCB porewater concentrations estimated based on batch leaching test C(TPCB)=0.266 mg/L

[B] - Layer 1 defines boundary of placed dewatered sediment, excluding reinforcing sand layer

Table 8
Groundwater Flux and estimated PCB Loss Along Eastern Boundary Due to Tidal Fluctuations

ESTIMATE OF PCB LOSS FROM RESULTS OF TIDAL SIMULATION

Boundary Liner	Total Outflow from Sediment to Sand cu-ft/day/(ft perimeter)[A]	Boundary of Offshore Sheeting Perimeter (ft)[B]	Flow Rate Exiting the Boundary (cu-ft/day)	Total Volume of Flow Exiting Boundary Over 30 Years (cu-ft)	Total Volume of Flow Exiting Boundary Over 100 Years (cu-ft)	Estimate of PCB Loss Exiting Boundary Over 30 Years (kg)[C]	Estimate of PCB Loss Exiting Boundary Over 100 Years (kg)[C]
lined	0.00013	1476	0.2	2,100	7,000	0.02	0.05
unlined	0.073	1476	107.7	1,200,000	3,900,000	9	11

[A] - Taken from Tidal Groundwater Model
[B] - Based on Current Perimeter of Sheeting Design
[C] - Porewater Concentration of 0.266 mg/L Estimated Based on Results of Batch Leaching Tests Conducted on Hydraulically placed Sediment (1500 to 2150 mg/kg TPCB)

6.0 REFERENCES

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